Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Challenges in ν-argon scattering and new results from the MicroBooNE experiment

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for the MicroBooNE collaboration
INT Workshop
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Outline

- **ν Oscillation phenomena**
  - Preparing for SBN & DUNE
  - Sketching out ν anomalies
- SBN & MicroBooNE
  - The LArTPC concept
  - MicroBooNE reconstruction approaches
- MicroBooNE first results
  - ν_μ CC charged particle multiplicities
  - ν_μ CC inclusive
  - ν_μ CCπ^0
- Emitted protons in ν-Ar scattering
- Double the beam, double the fun!
- Summary

ν Oscillation phenomena

$$P(\nu_\alpha \to \nu_\beta) = F(U_{PMNS}, \Delta m^2_{ij}, E_{\nu_\alpha}, L)$$

$$\downarrow$$

$$\Phi^{produced}_{\nu_\alpha}(E_{\nu_\alpha}) \otimes \sigma^{produced}(E_{\nu_\alpha}) \otimes \varepsilon^{produced}(E_{\nu_\alpha})$$

$$\Downarrow$$

$$\Phi^{propagated}_{\nu_\beta}(E_{\nu_\beta}, \theta, \Delta m^2, \delta) \otimes \sigma^{propagated}(E_{\nu_\beta}) \otimes \varepsilon^{propagated}(E_{\nu_\beta})$$

Connecting **produced** and **propagated** neutrinos requires the knowledge of flux and cross section along its energy spectra.

$$\frac{N^{propagated}_{events}(E_\nu)}{N^{produced}_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

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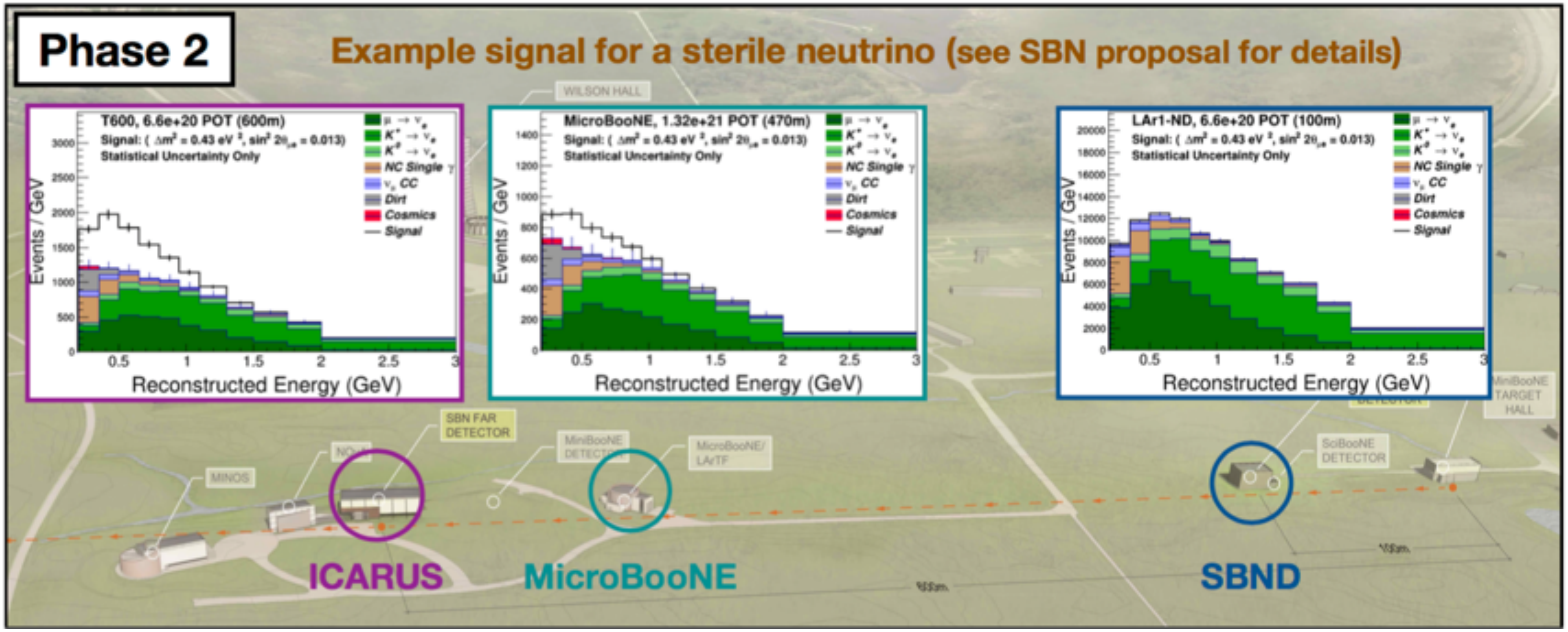
$$\Phi^{produced}_{\nu_\alpha}(E_{\nu_\alpha}) \otimes \sigma^{produced}(E_{\nu_\alpha}) \otimes \varepsilon^{produced}(E_{\nu_\alpha})$$

$$\Phi^{propagated}_{\nu_\beta}(E_{\nu_\beta}, \theta, \Delta m^2, \delta) \otimes \sigma^{propagated}(E_{\nu_\beta}) \otimes \varepsilon^{propagated}(E_{\nu_\beta})$$

To achieve accurate oscillation measurements the knowledge of how neutrinos are produced and how they interact with the matter are an essential piece of the program.

$$\frac{N^{propagated}_{events}(E_\nu)}{N^{produced}_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

Preparing for SBN & DUNE

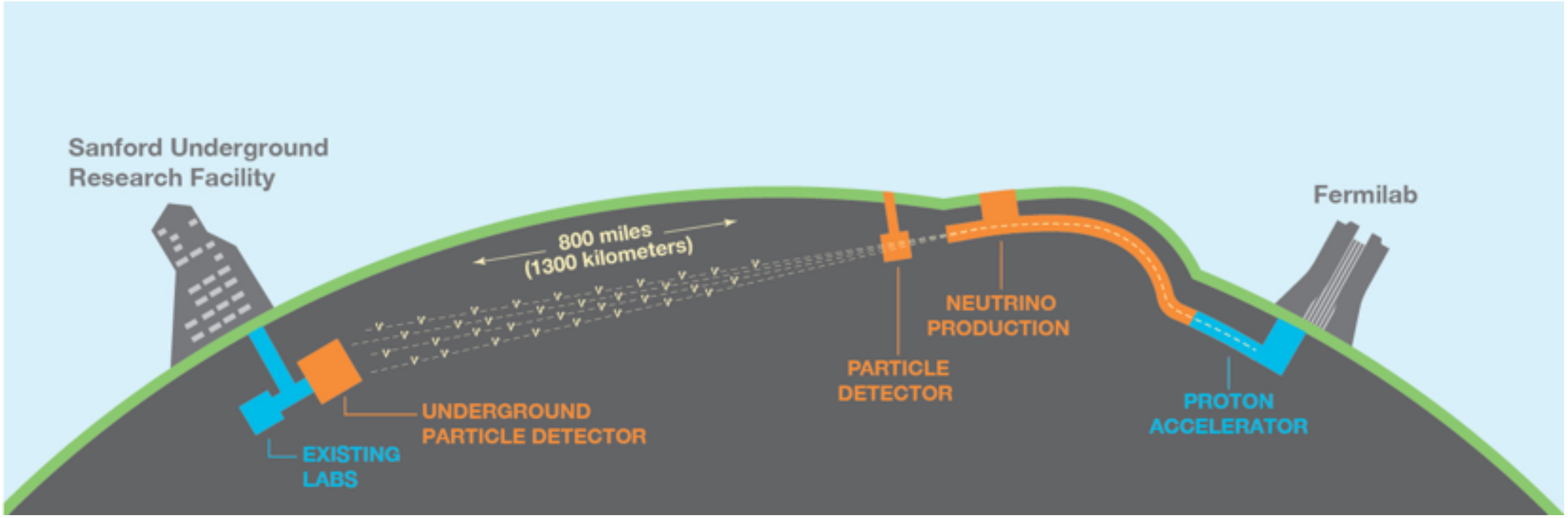


SBN will study the short baseline anomalies in the neutrino sector.
SBND, as near detector, will take a **huge amount of data** which will benefit of MicroBooNE studies in several aspects:

- understand which are the main backgrounds for ν_e selections in LArTPC
- event generator model choices
- understand reconstruction approaches

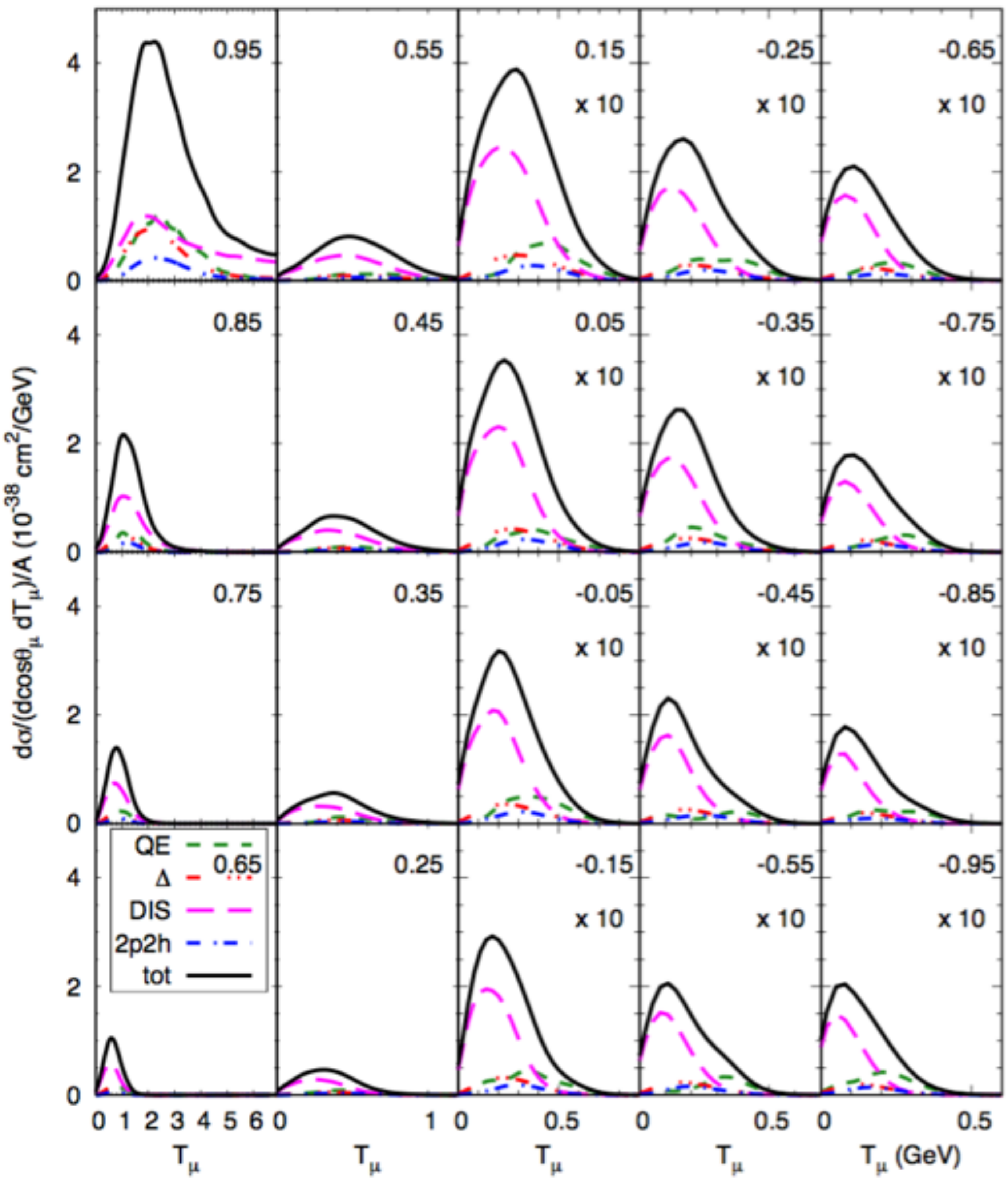
SBND will be able to perform more multi-dimensional differential measurements

Preparing for SBN & DUNE



On its main goals, DUNE aims for measuring with exceptional accuracy and precision ν oscillations allowing for understanding CP phenomena.
It requires a deep knowledge of neutrino and anti-neutrino interactions in argon for ν_μ and ν_e.

Preparing for SBN & DUNE



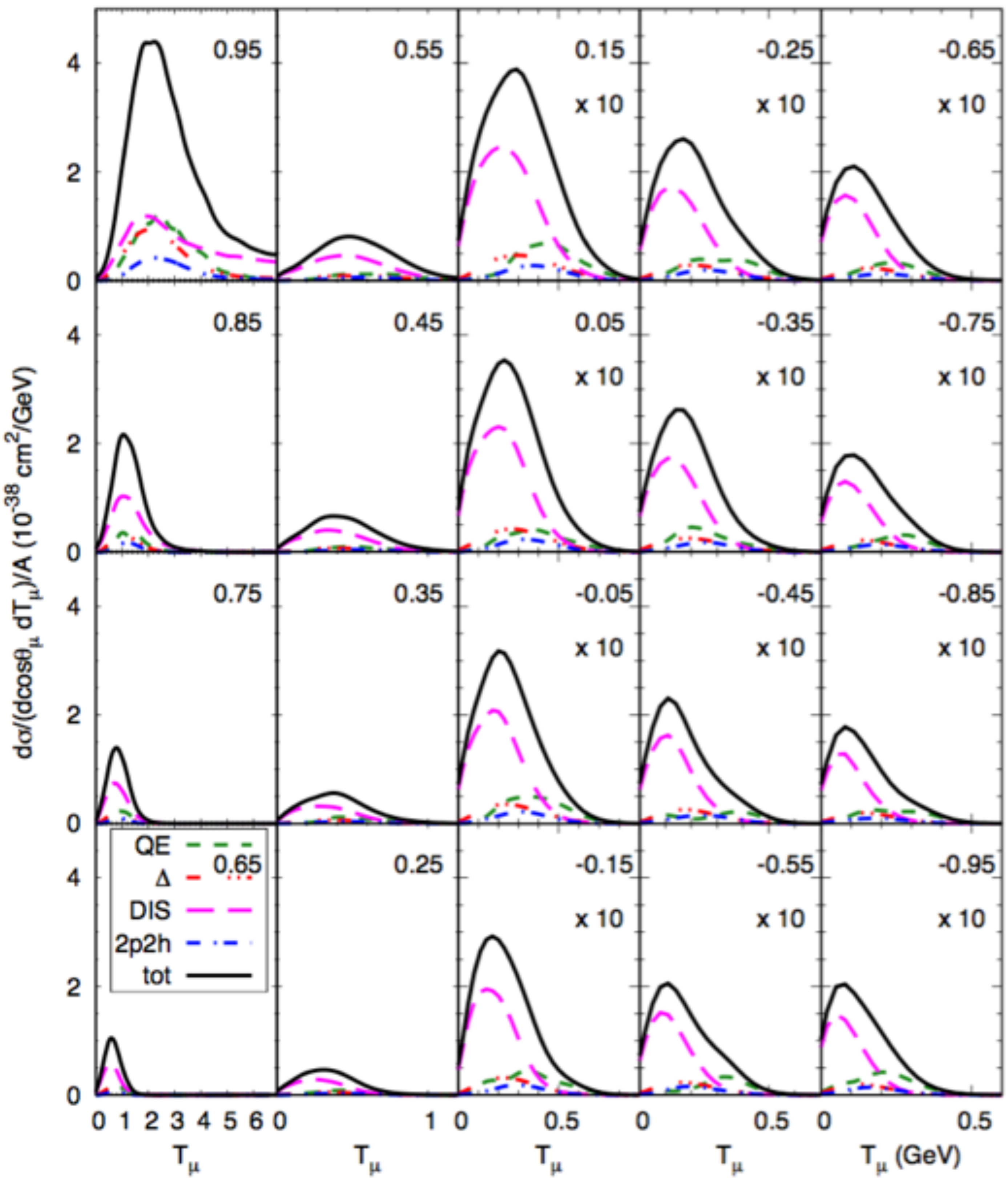
U. Mossel et al., Phys.Rev. C94 (2016) no.3, 035502

Prediction from **GiBUU** on ν_μ CC from LBNF beam.

- Dominant reaction is DIS, which makes understanding hadron production and absorption in argon important.
- QE regions appear with lower components but at higher μ energy than DIS.

To estimate the initial neutrino energy accurately we need to understand which fraction of the event can get measured (final topology=observable) and which is its original neutrino process(=non-observable).

Preparing for SBN & DUNE



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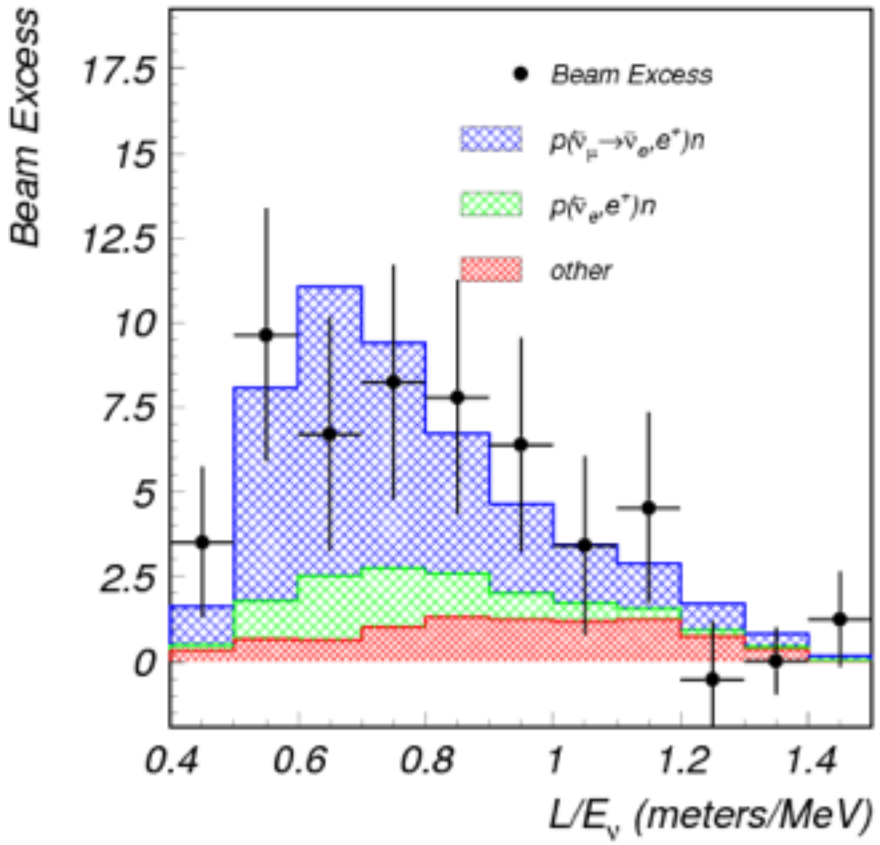
Prediction from **GiBUU** on ν_μ CC from LBNF beam.

- MicroBooNE & SBN will provide <u>unique studies on ν-induced hadron production and absorption in argon</u>.
- They cover the <u>lower energy spectrum</u> which is fundamental for the <u>understanding of FSI</u> which may be of biggest impact at this region.
- While as well providing answers to <u>neutrino anomalies in the short baseline paradigm</u>.

We measure ν-Ar observables

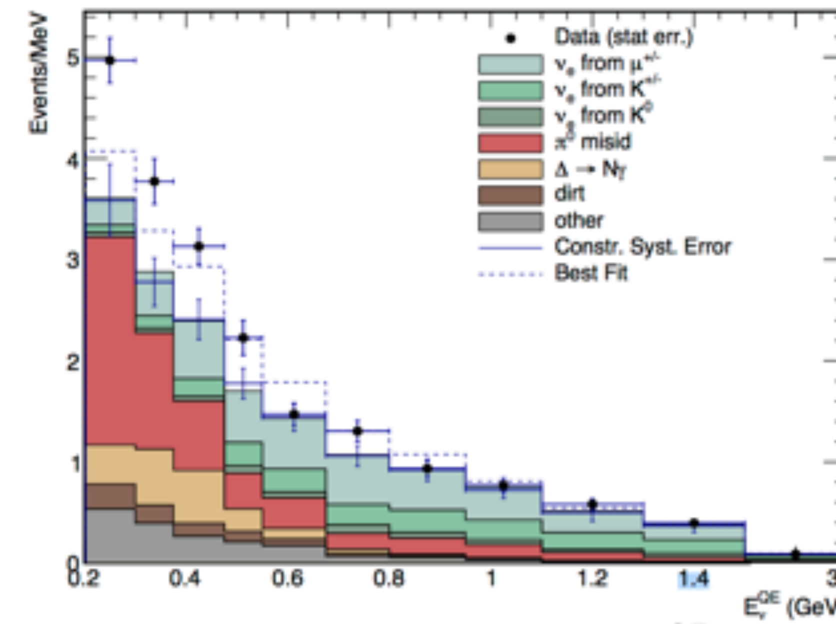
Sketching out ν anomalies

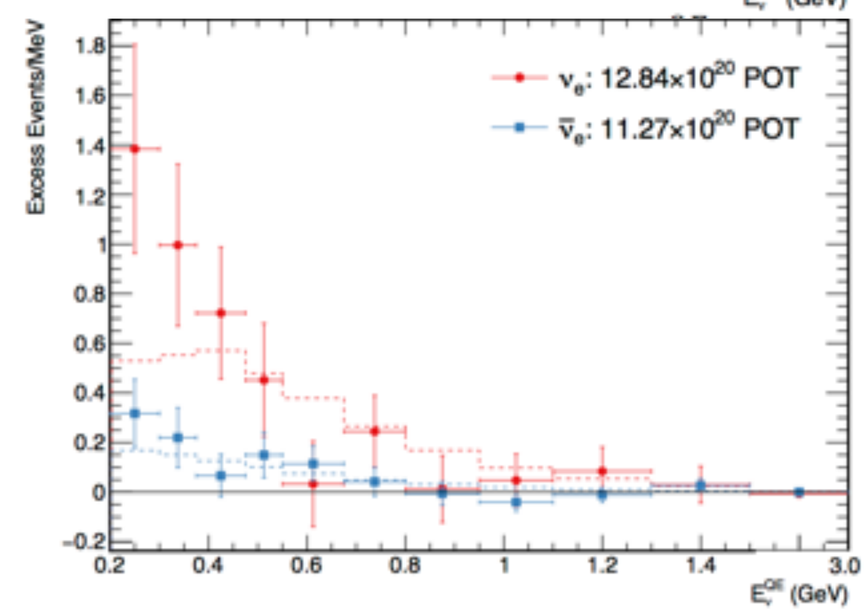


Phys.Rev. D64 (2001) 112007

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e?$

arXiv:1805.12028





The uB/SBN commitment:

- Clear identification of $e^{+/-}$/photon.
- Better constraints in ν-nucleus scattering by lowering particle detection thresholds.
- Better characterization of final state particles.

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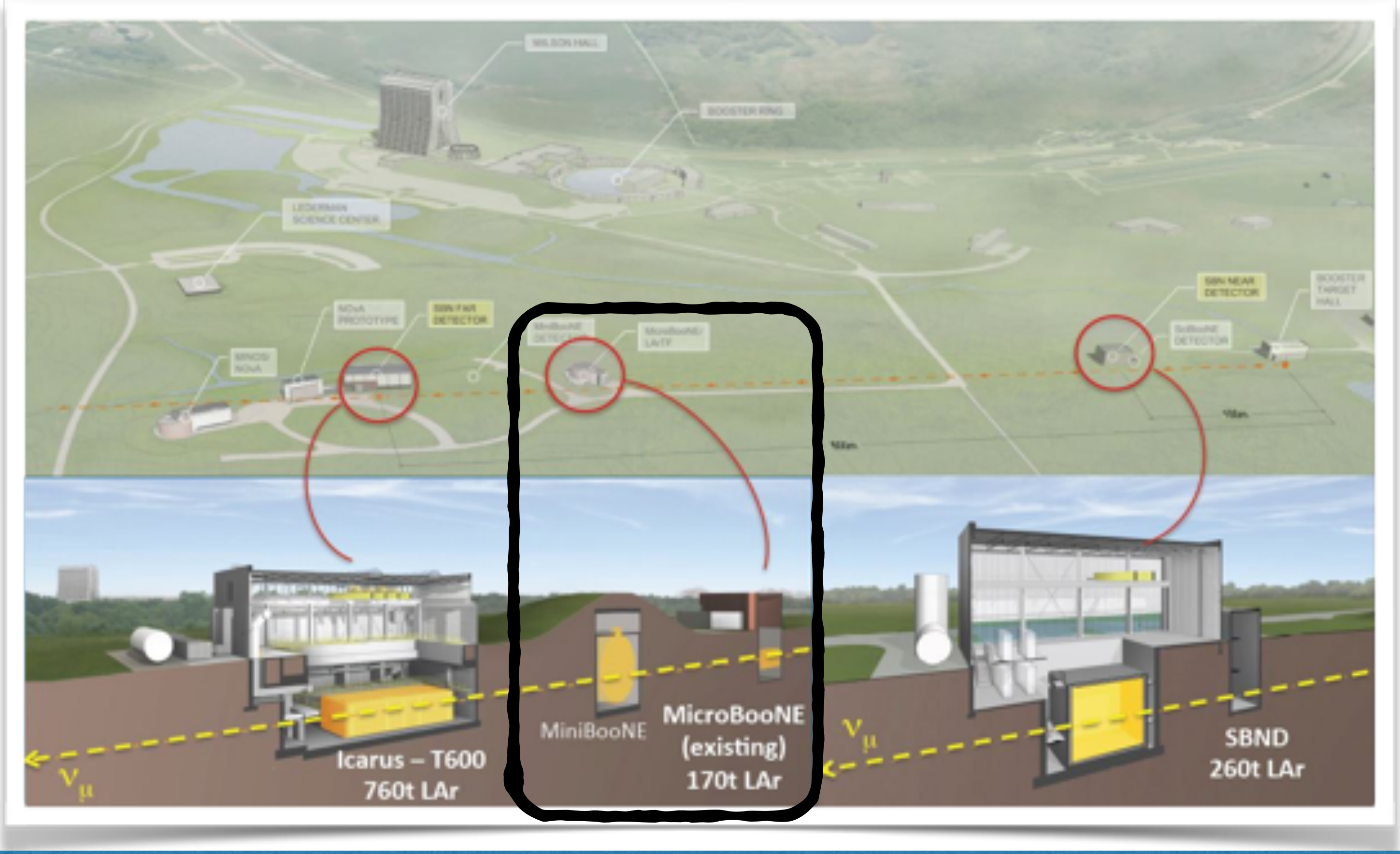
SBN & MicroBooNE

SBN (Short Baseline Neutrino) aims to search for non-standard ν oscillations by ν_e appearance and ν_μ disappearance with unprecedented precision in BNB.



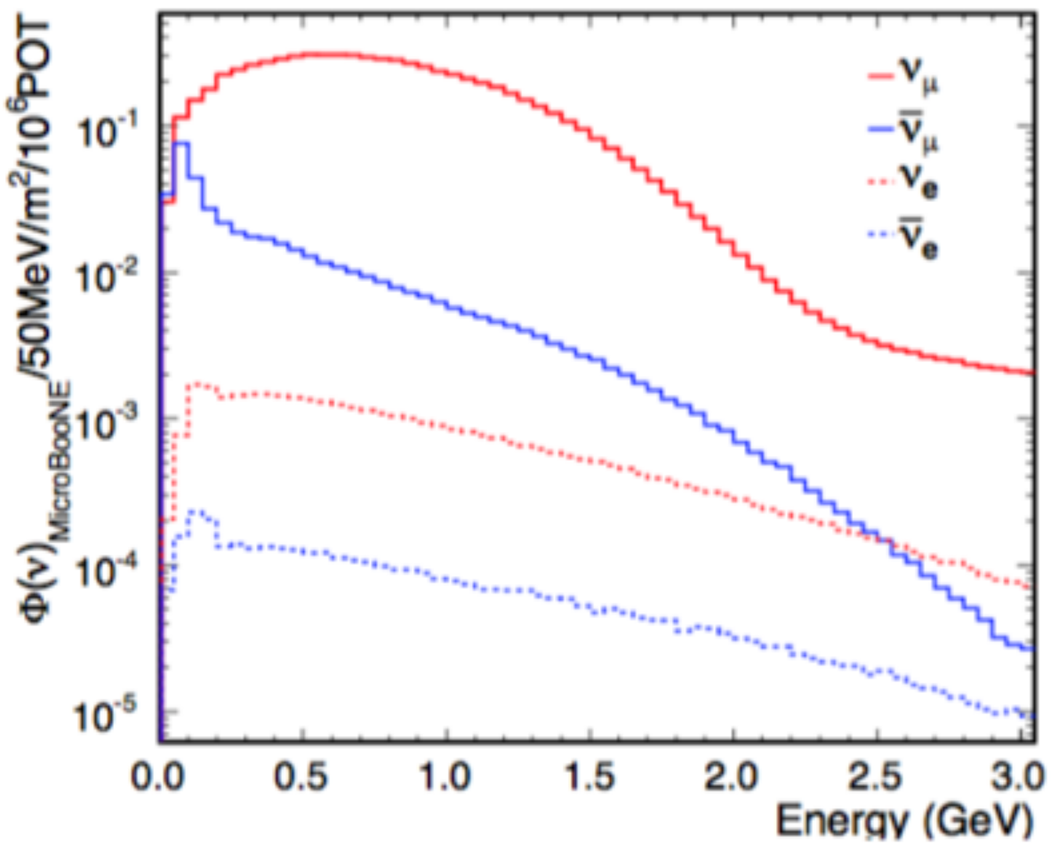
Main MicroBooNE physics goals:

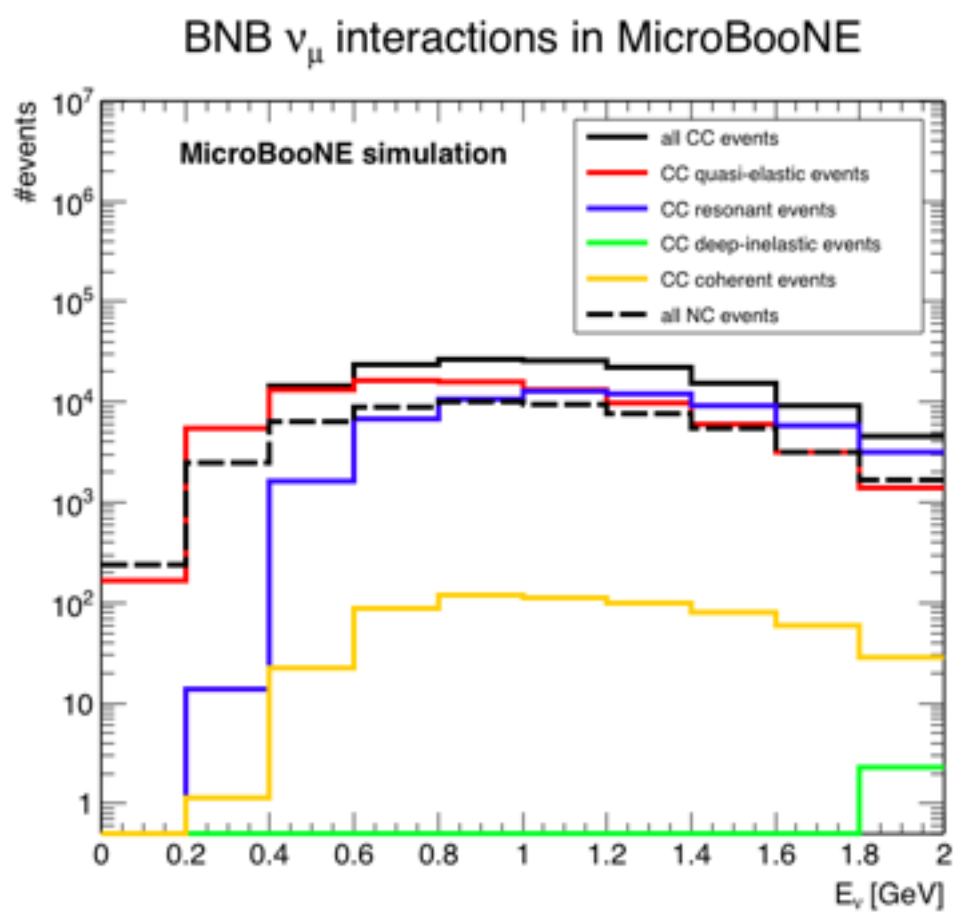
- Investigate MiniBooNE low- energy un-predicted data (ν_e CC events?)
- Measure first high statistics ~1GeV ν-Ar cross sections
- R&D for Deep Underground Neutrino Experiment (DUNE)
- Joint oscillation analysis within the SBN program

+ Exotic physics capability studies (proton decay, heavy sterile ν, SN).

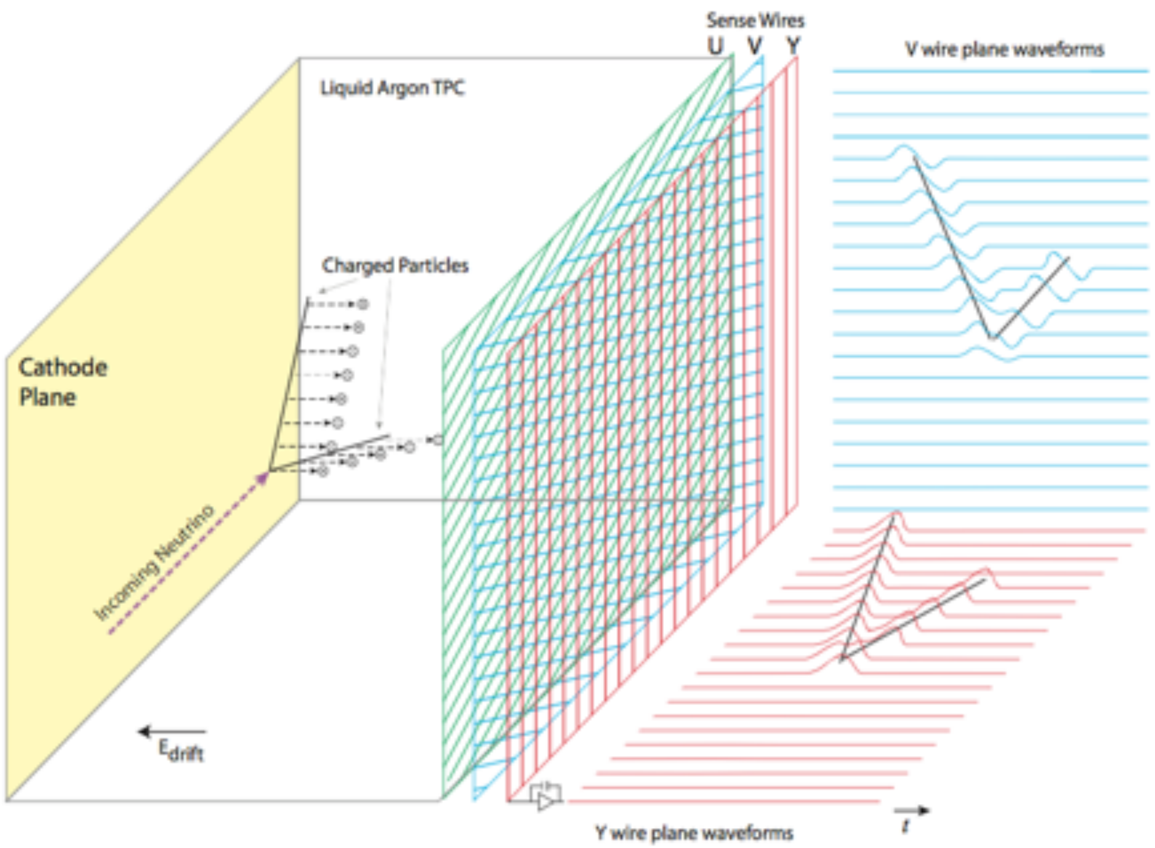
ν Flux @ MicroBooNE

8 GeV Protons from BNB
Almost pure ν_μ beam (0.5% intrinsic ν_e contamination at uB)





The LArTPC concept



- Charge particle detection by collection of **ionization** charge (0.273 kV/cm electric field).
- 3D event reconstruction by combining signals from all planes (2 required)
- **Scintillation** light can be used to correct for ionization electron lifetime effects from improved calorimetry.

The MicroBooNE detector:

- 170 tons of liquid argon : 86 tons of active mass
- Two induction planes (U, V) and one collection plane (Y), 3 mm pitch, 3mm separation between wires
- Near-surface operation: adding cosmic rays into the game!

Huge efforts on simulation, reconstruction and calibration: several public technical notes and papers produced during the first 3 years of data taking. **First cross section results!**

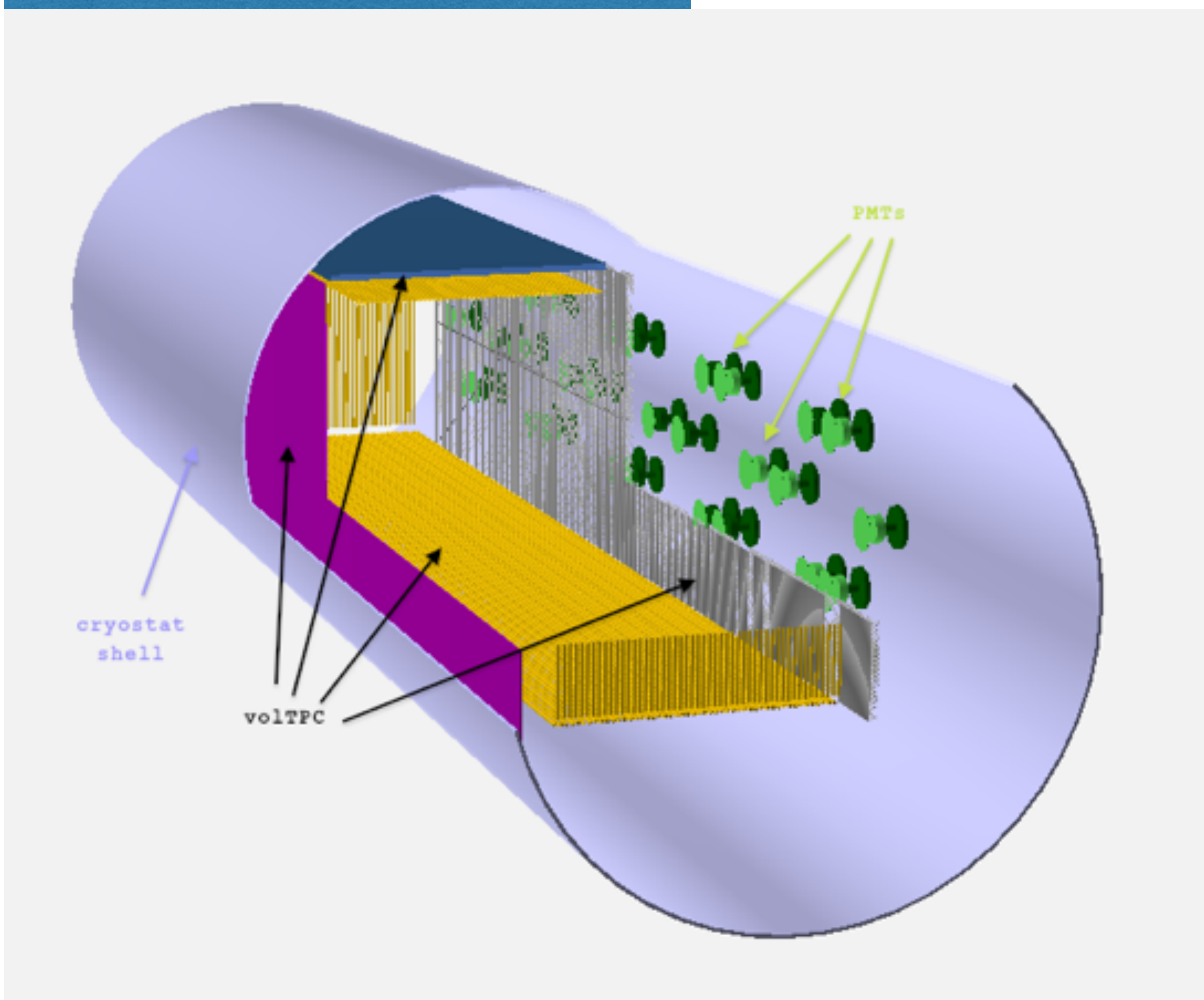
Sharing efforts with the other SBN detectors and LArIAT (our main test-beam experiment which also includes important physics goals for the program).

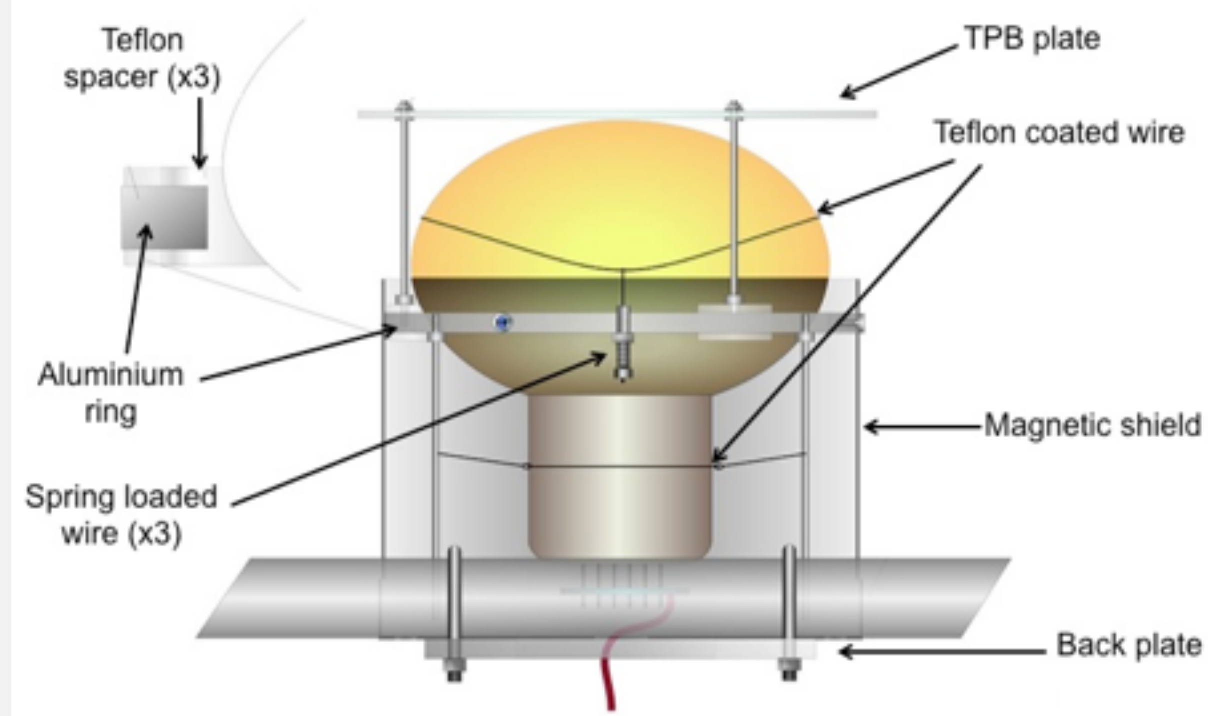
Our main neutrino event generator is GENIE, detector simulation uses Geant4.

arXiv:1609.06169 [physics.ins-det]

MicroBooNE Photon Detectors

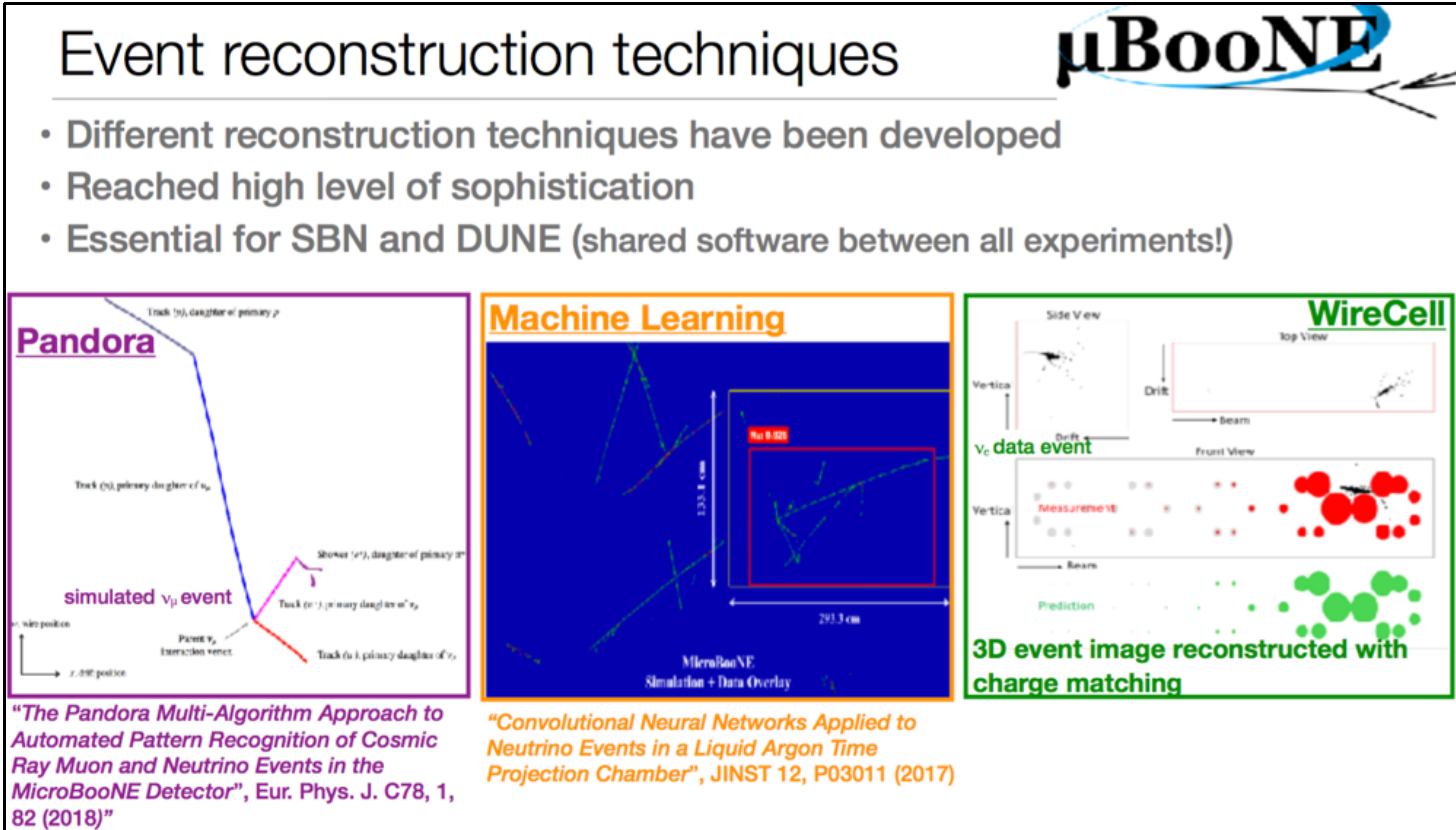
32 PMTs + 4 scintillator bars





Scillintillator light allow us to identify neutrino interaction presence wrt cosmic rays.
Other LArTPC, as SBND, will test higher coverage to allow for very low momentum particle identification.

MicroBooNE reconstruction approaches

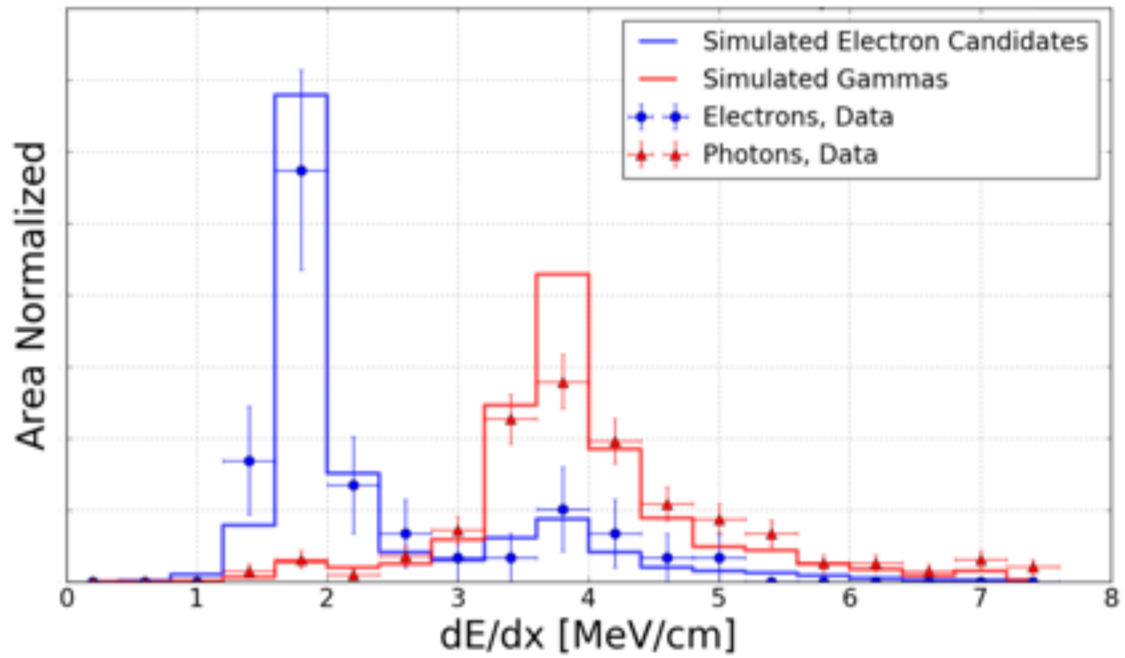


From Roxanne Guenette @NEUTRINO2018

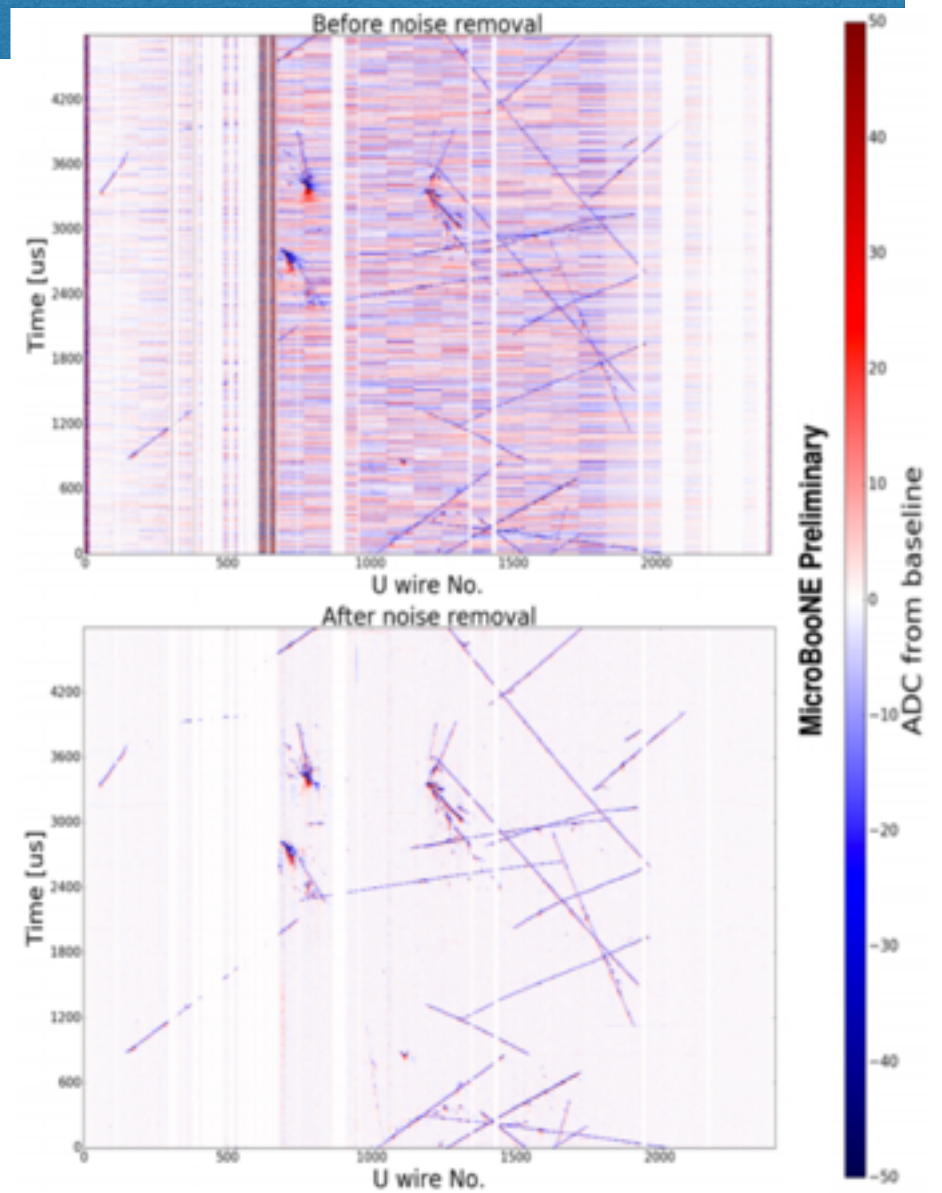
MicroBooNE reconstruction approaches

Momentum reconstruction:

- For contained particles in the detector can be achieved by using momentum-by-range or calorimetry.
- For particles leaving the detector it is performed using multiple Coulomb scattering (decreased resolutions with respect to contained tracks).
- Continuously working on improving reconstruction and achieve lower energy thresholds, particularly important for protons.
- Improving shower reconstruction resolution, **e/γ separation** capabilities
- 4π acceptance



ArgoNeut experiment, arXiv:1610.04102



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MicroBooNE first results

MicroBooNE has been concentrated on understanding the detector, developing tools, calibration and drawing the path to build a robust ν_e measurement at the BNB beam.
First physics results are focused on understanding **ν_μ CC interactions** with its main challenges:

- ν_μ CC charged particle multiplicity measurement
- ν_μ CC differential cross section measurement
- ν_μ CCπ^0 total cross section measurement

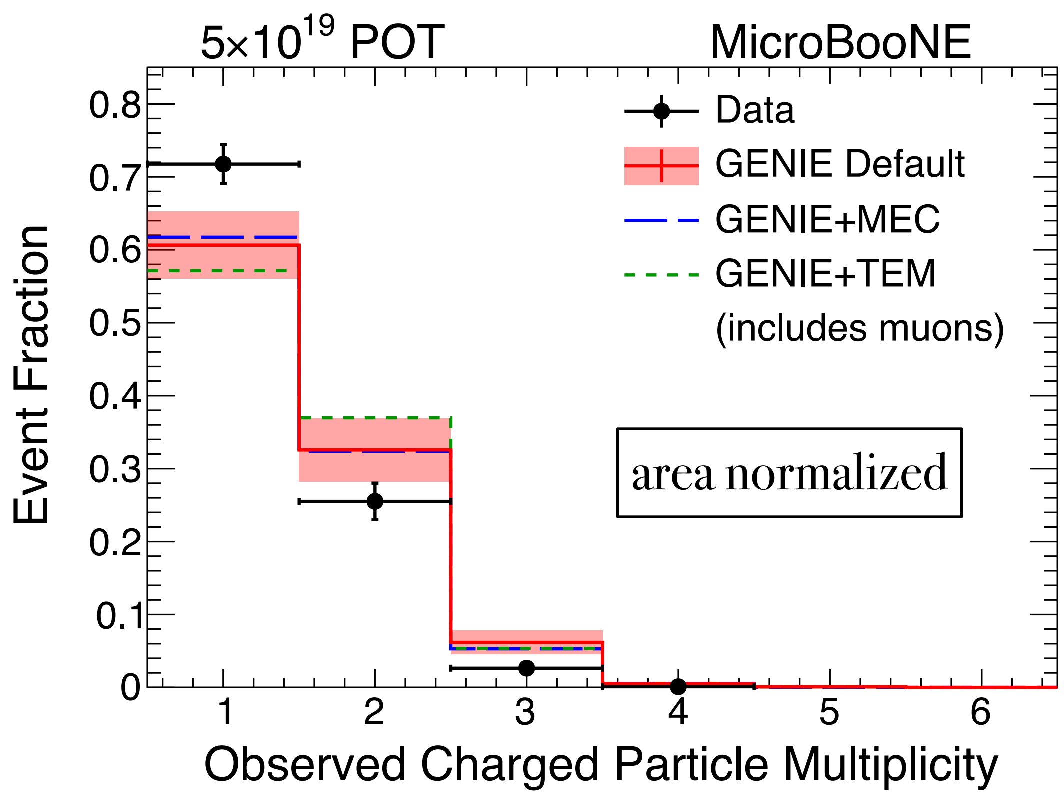
- **ν_μ CC** is our first step to understand our major signal and its simulation.
- It is comparable across models and experiments due to its simplicity in the signal definition.

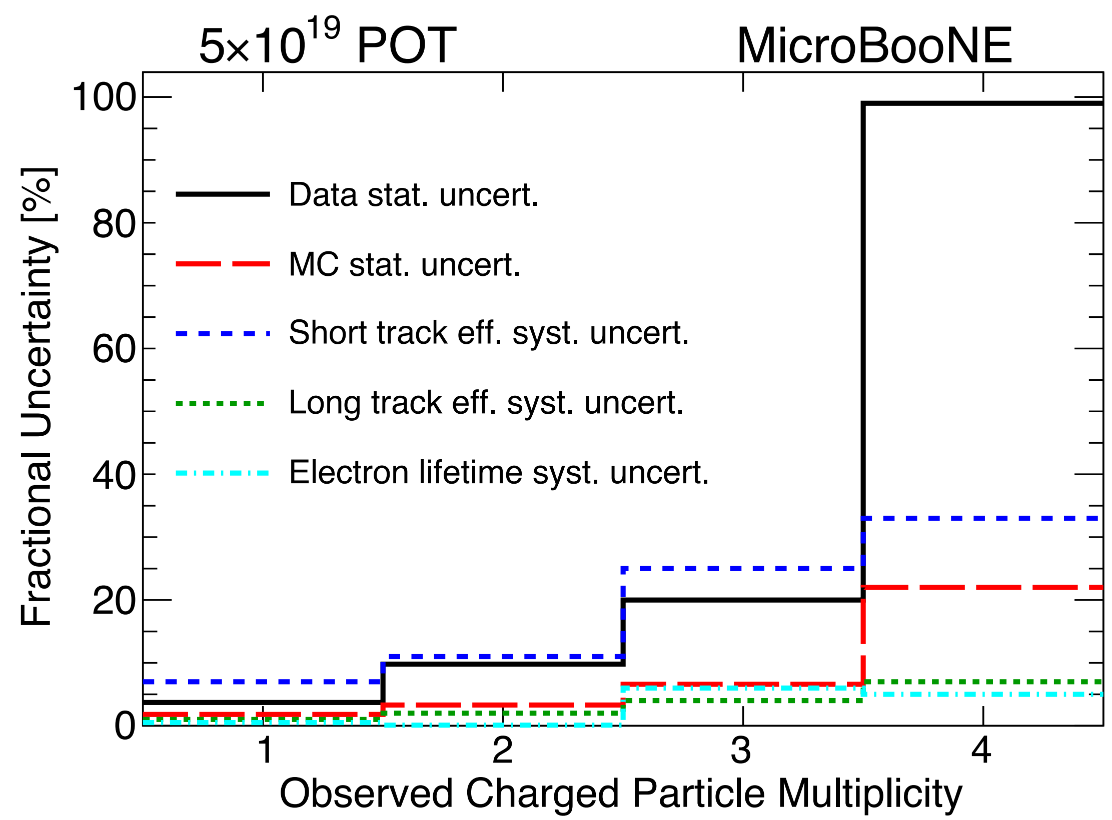
- **ν_μ CCπ^0** represents our efforts and builds the path towards shower reconstruction and electron/gamma separation.

- Essential for ν_e measurements and comprehension of traditional ν_e searches backgrounds.

ν_μ CC charged particle multiplicity measurement

Its main goal is to understand how our direct observables (final state particles) are represented by the simulation.
Represents a first big step on understanding how a final event *visible energy* measurement can be biased due to excess/deficit of final state particles. Strongly sensitive to FSI.
For this first measurement, a conservative particle threshold has been applied.





"Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions", arXiv:1805.06887, submitted to PRD (2018)

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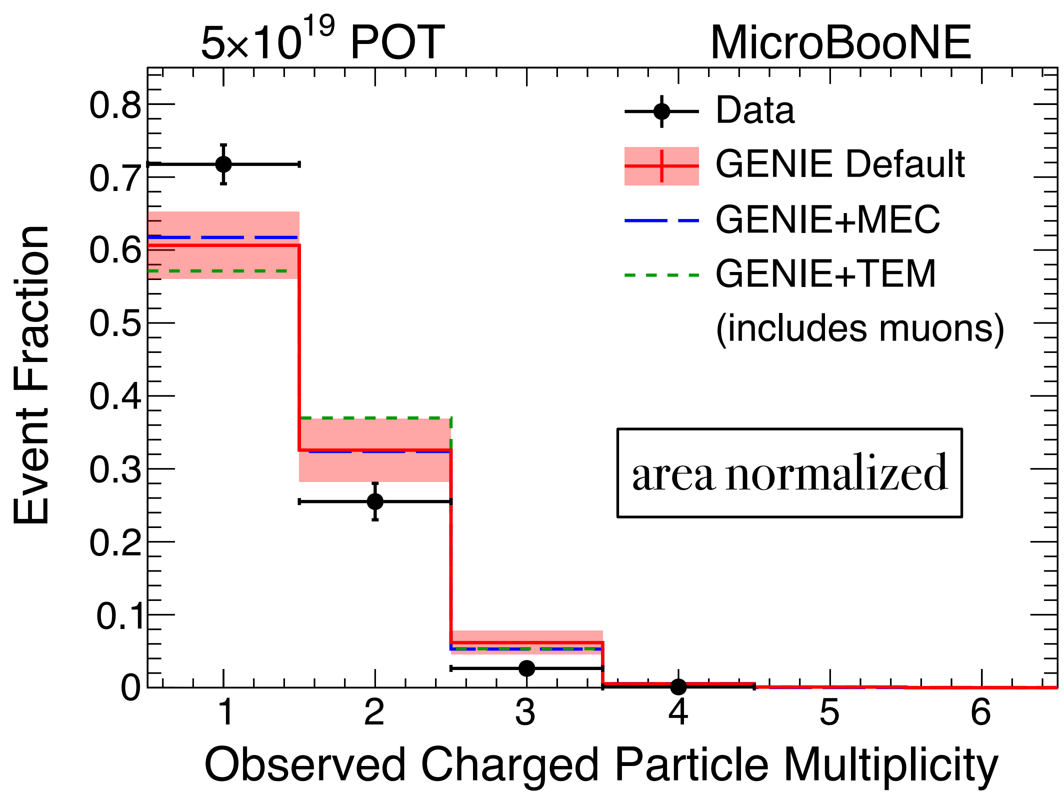

Observed migration of events along different multiplicities.

- Indication on FSI underestimating hadron absorption?
- Overestimation of nucleon knock out?
- Detector simulation?

Next steps includes a **CCNProton (N>0)** measurement to understand simulation of final state protons.
We need to incorporate more semi-inclusive investigations: **CCNProton (N>=0)**.

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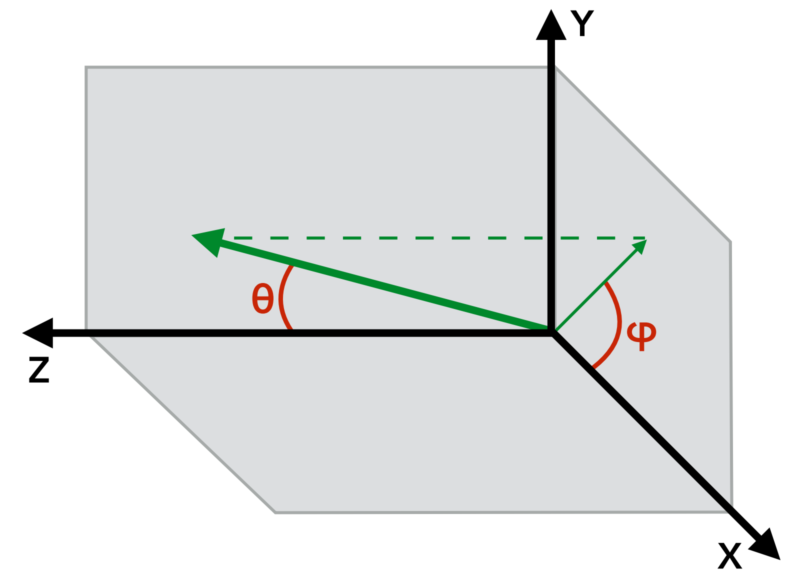
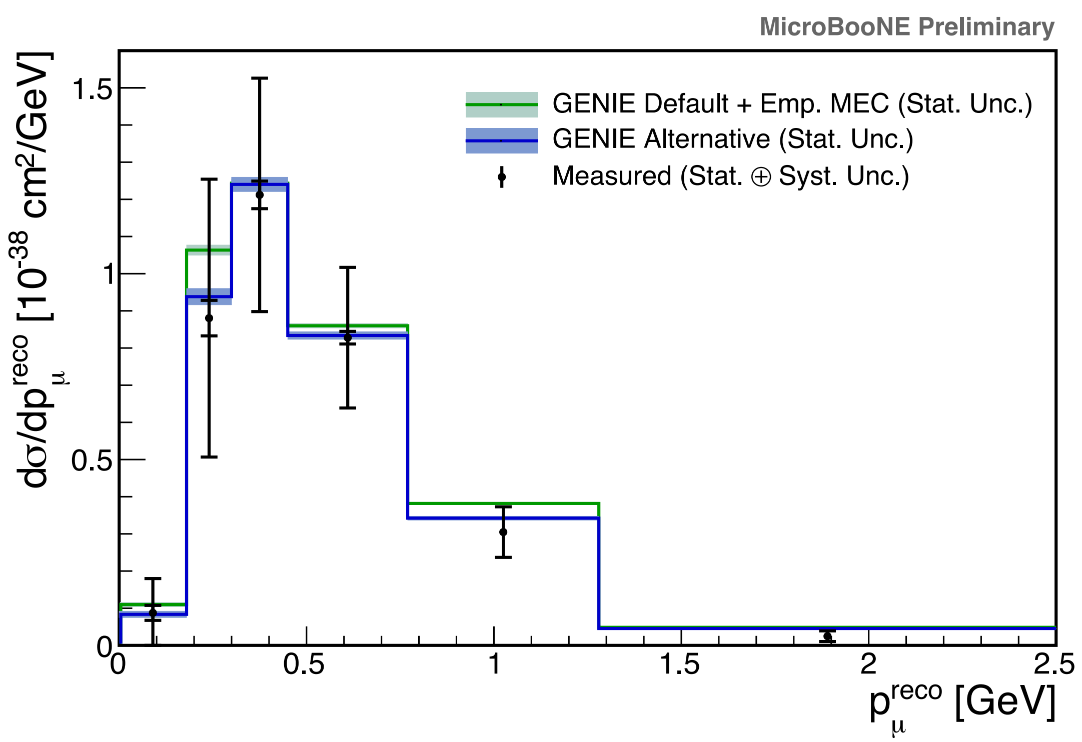
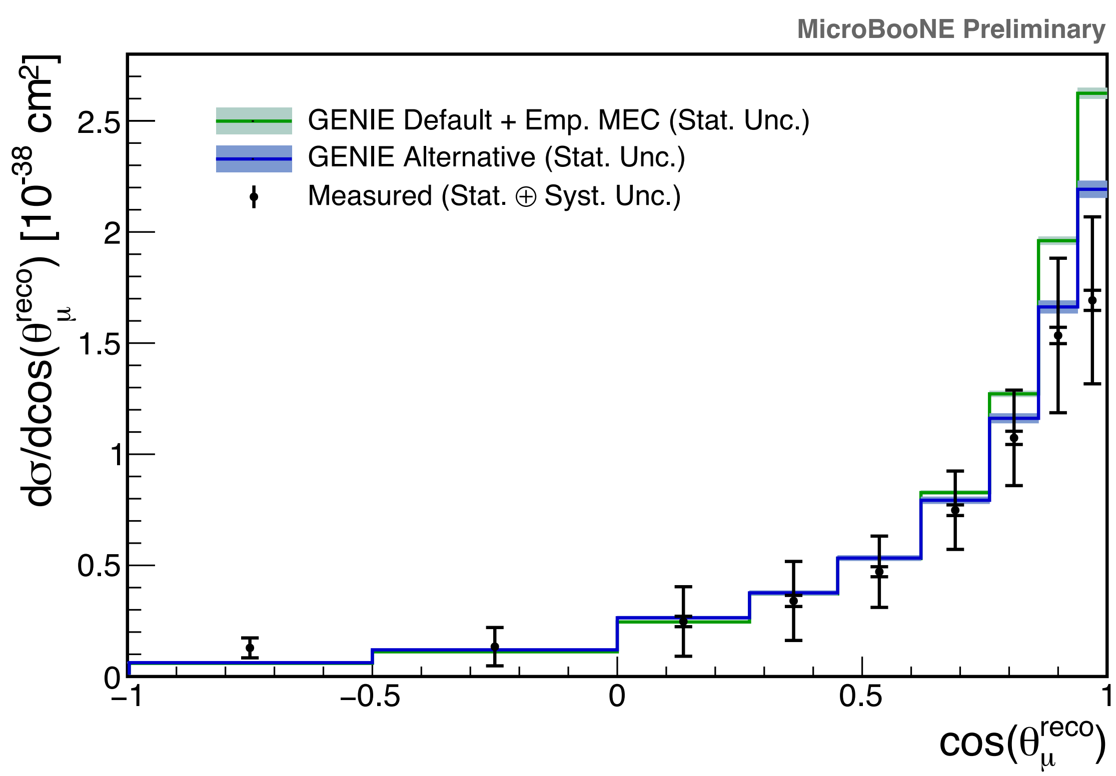
ν_μ CC differential cross section measurement

This analysis applies an improved selection strategy which increases efficiency on the signal.
Single differential measurements on μ kinematics have been presented at NEUTRINO2018 while current work is focusing on providing double differential measurements.

Provided measured cross section with efficiency correction and without unfolding.
Covariance matrices and data release will be released to allow comparisons to different models.







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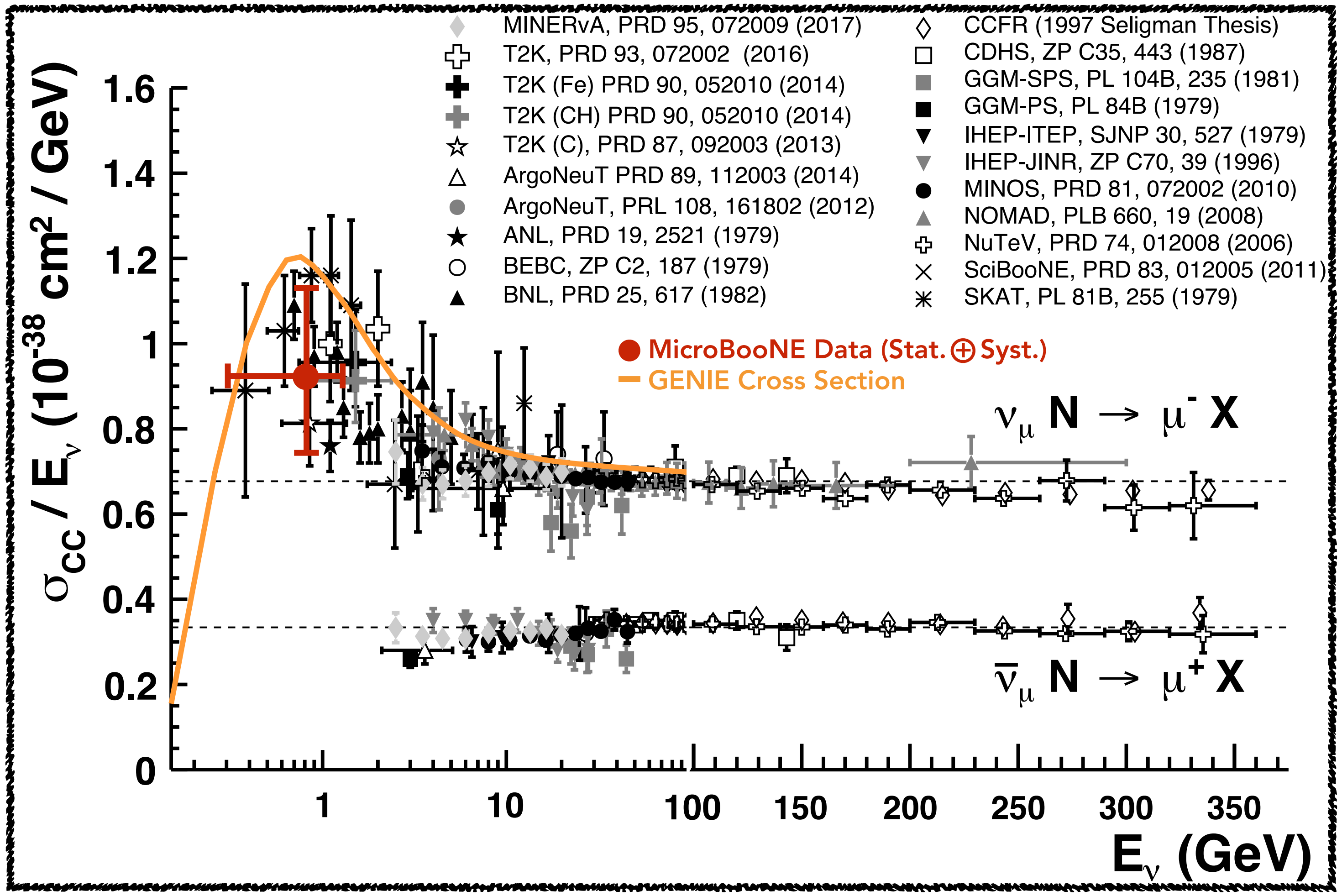
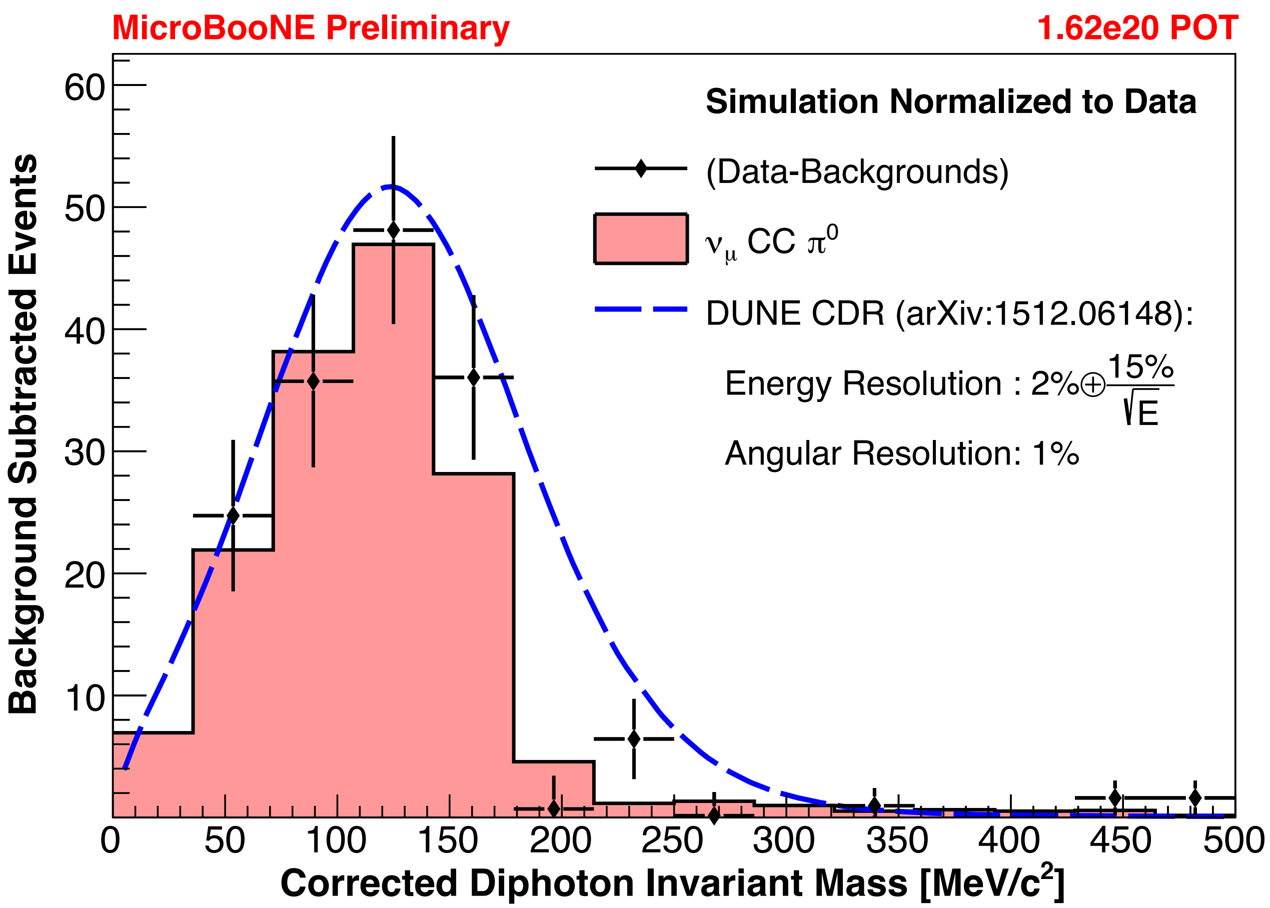
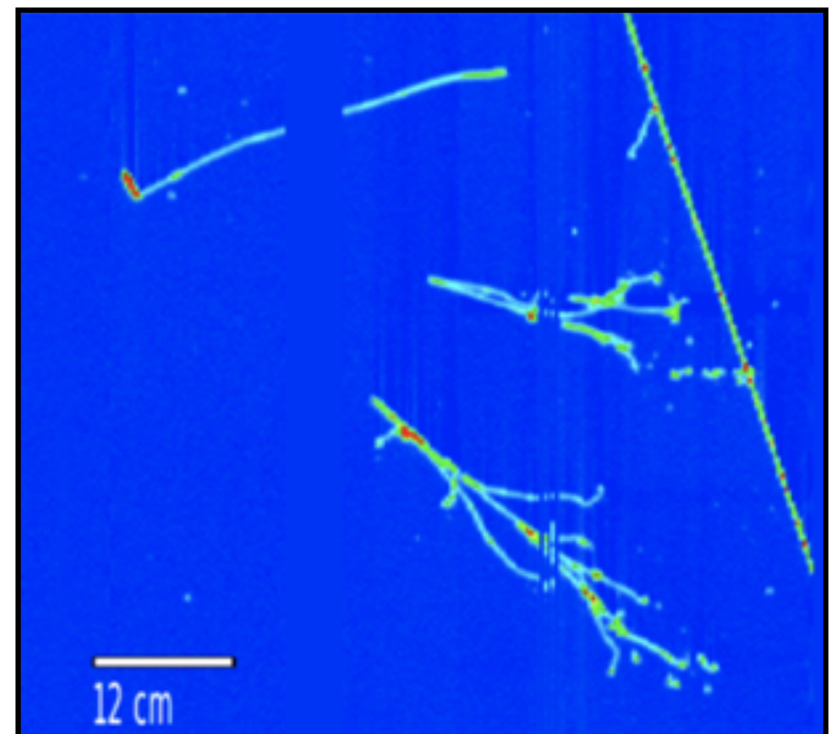
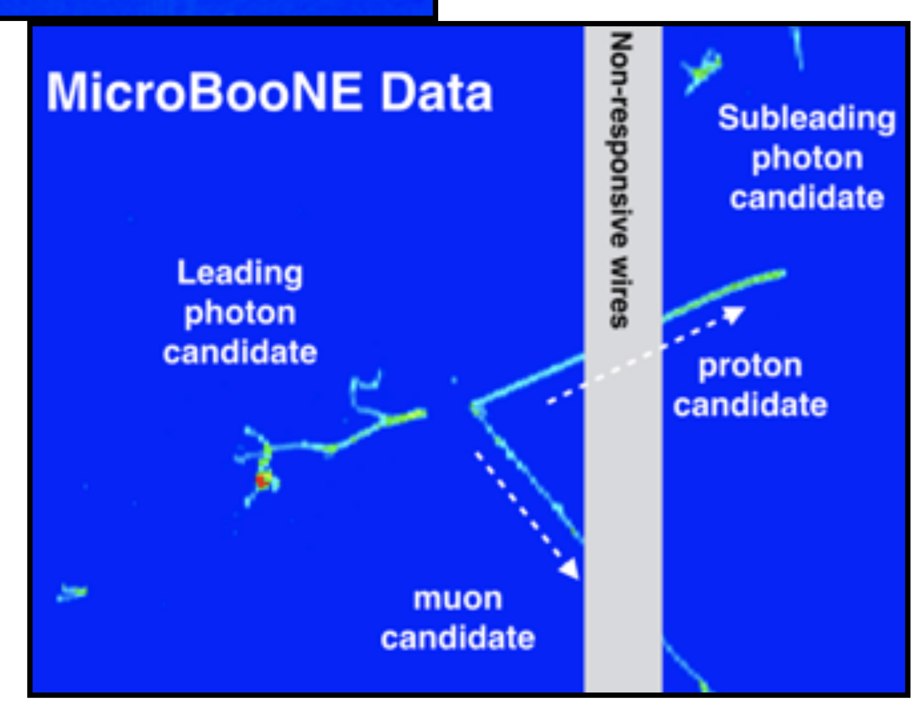


ν_μ CCπ^0 total cross section measurement

First steps into shower reconstruction and electron/gamma separation.
Allow us to identify next improvements for reconstruction of showers and its energy calibration:
We will produce differential measurements on ν_μ CCπ^0 and NCπ^0cross section!







Reconstruction of pi0 mass peak

ν_μ CCπ^0 total cross section measurement

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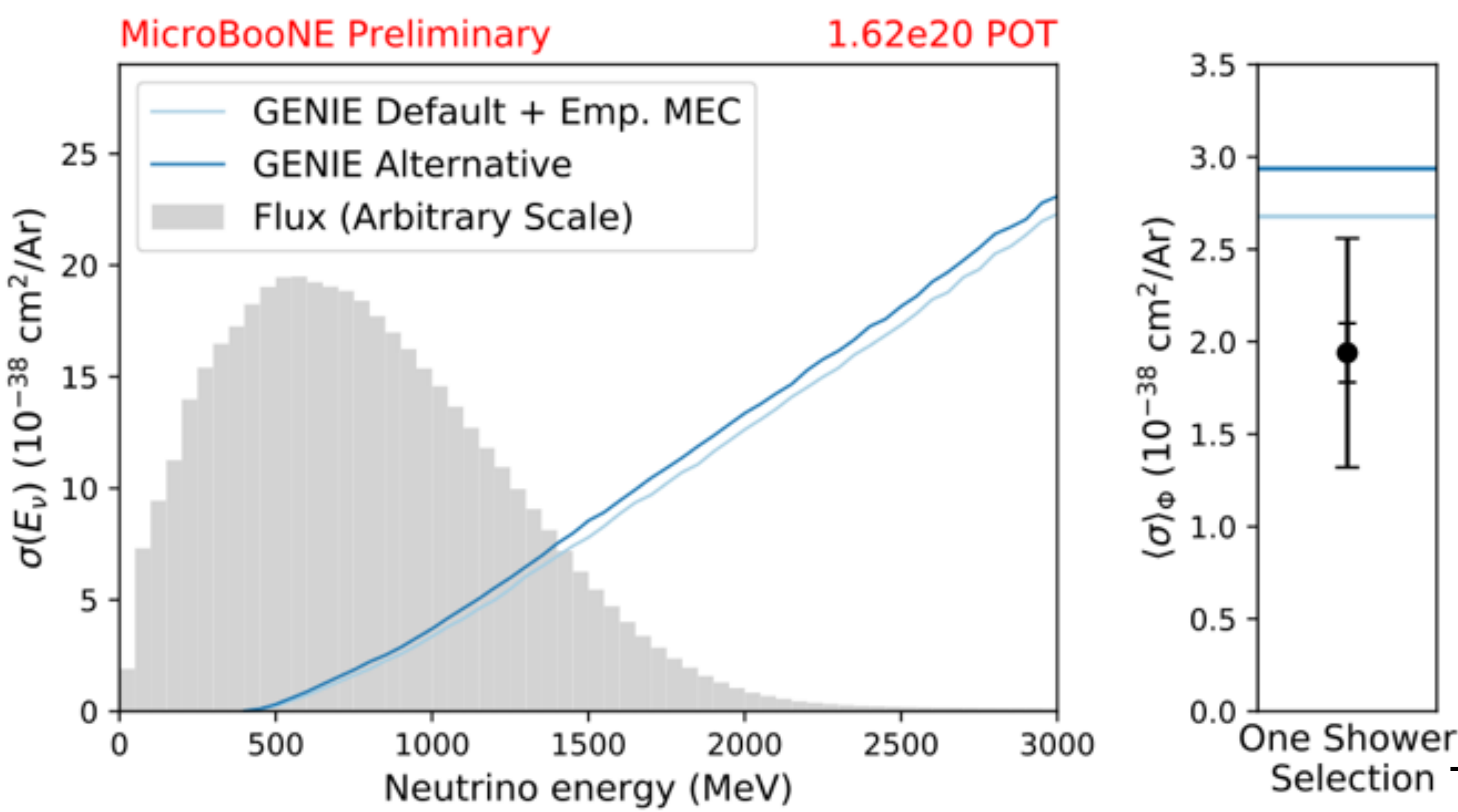

→ at least 1 shower

$$\left\langle \sigma^{\nu_\mu \mathbf{CC}\pi^0} \right\rangle_\Phi = (1.94 \pm 0.16 \text{ [stat.]} \pm 0.60 \text{ [syst.]}) \times 10^{-38} \, \frac{\text{cm}^2}{\text{Ar}}$$

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Emitted protons in ν-Ar scattering

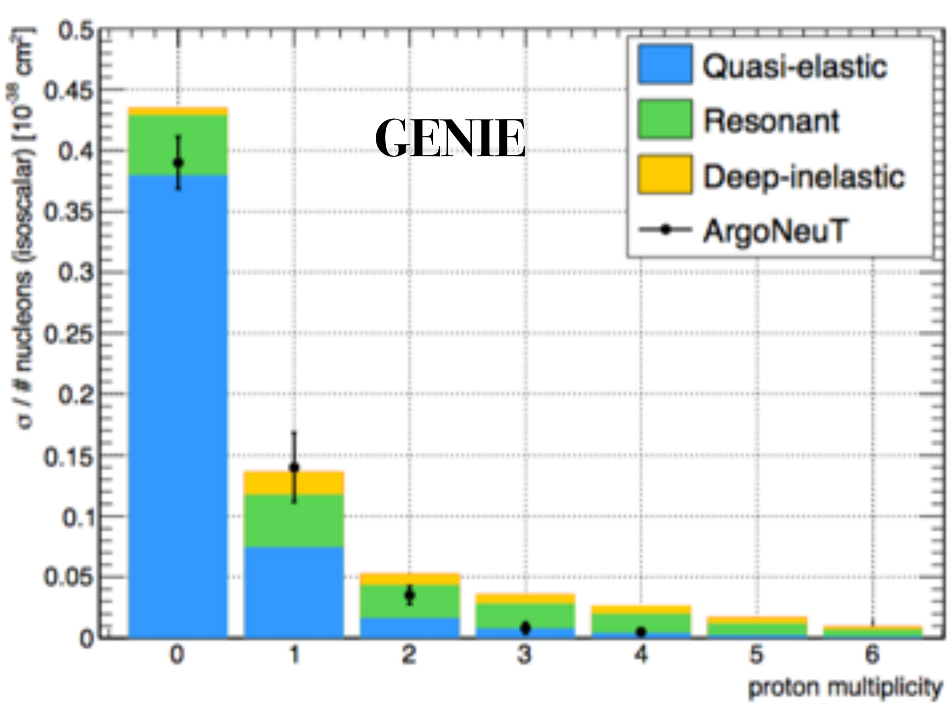
MicroBooNE is working on exclusive proton enhanced selections:

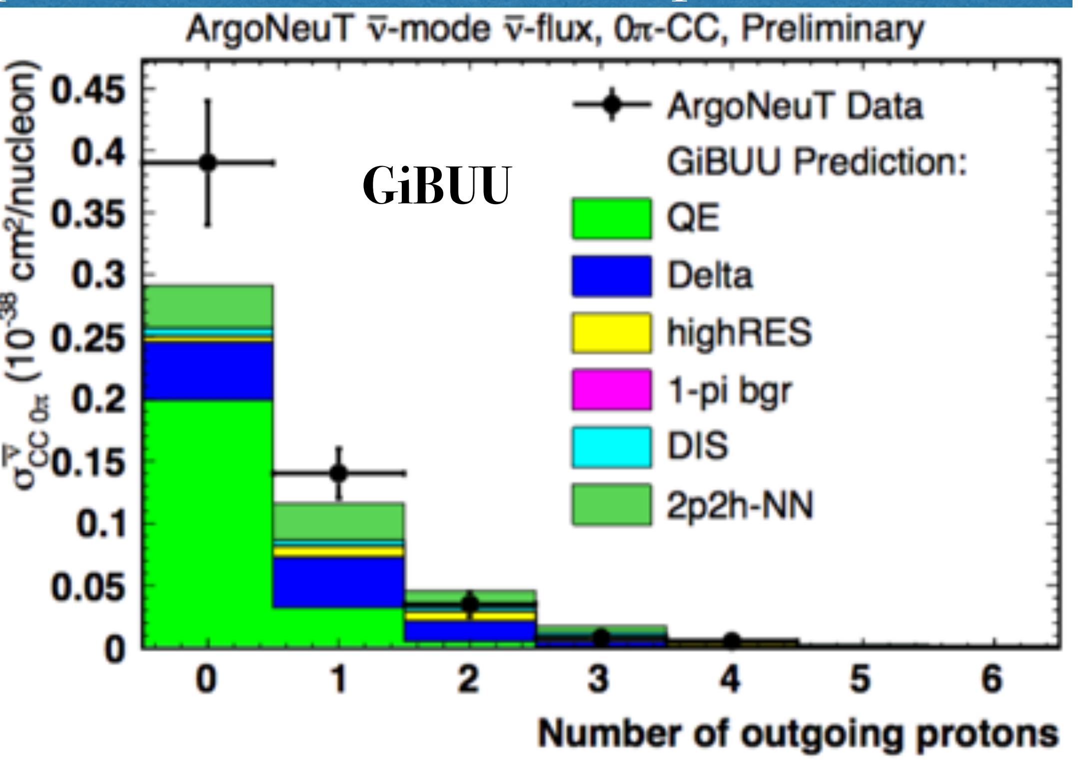
- **NCE**
- **ν_μ CCNProton (N>0)**: focusing on proton multiplicities
- **ν_μ CC1Proton**: constraint on ν_e appearance searches
- **ν_μ CC2Protons**: enhances specific effects as MEC and pion absorption

The main purpose is to understand nucleon emission on ν-Ar, including

- MEC
- Pion absorption
- SRC

We need to understand nucleons and MicroBooNE can understand protons in particular. One of our challenges is to lower the proton threshold as much as possible.





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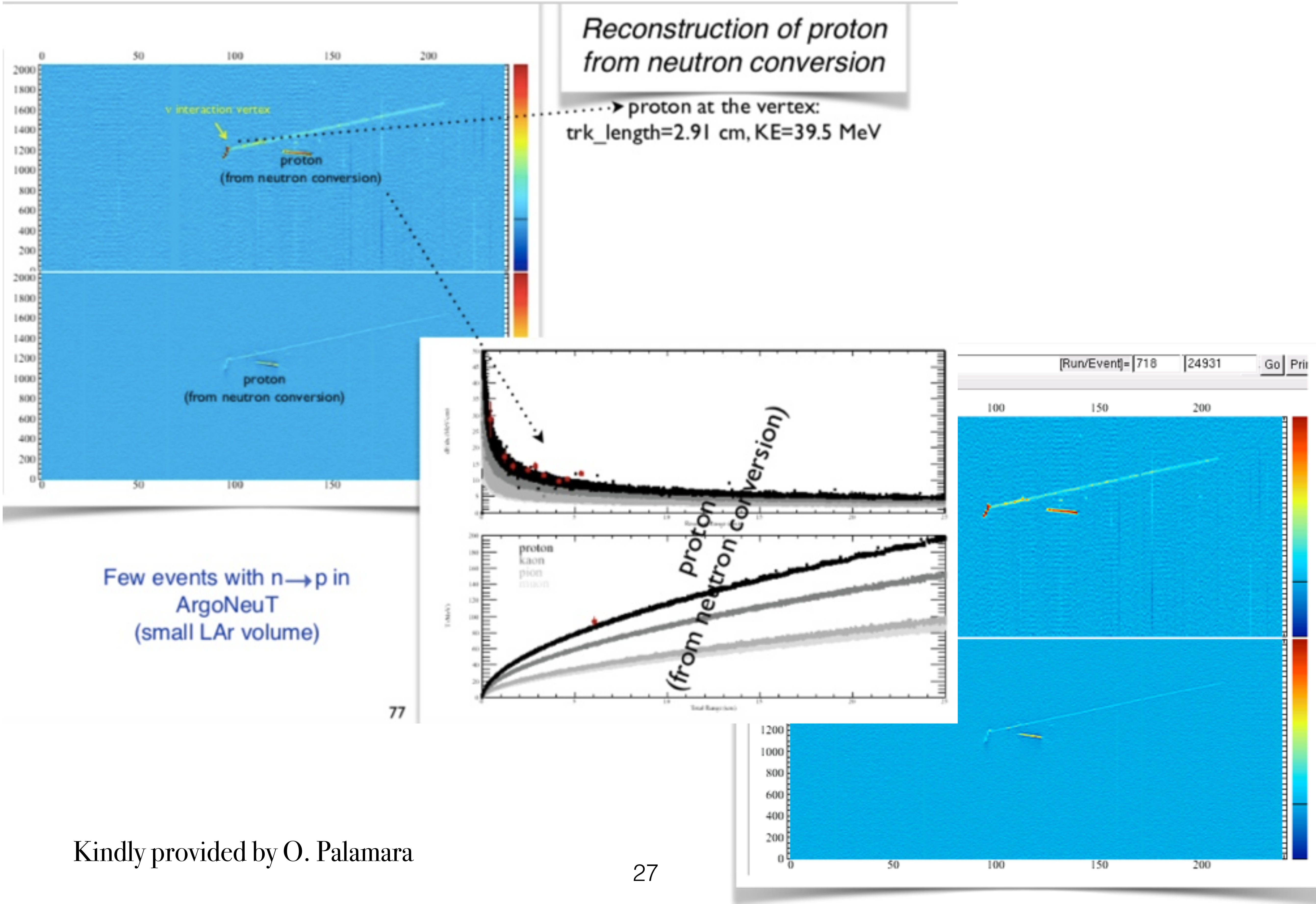

Kindly provided by O. Palamara

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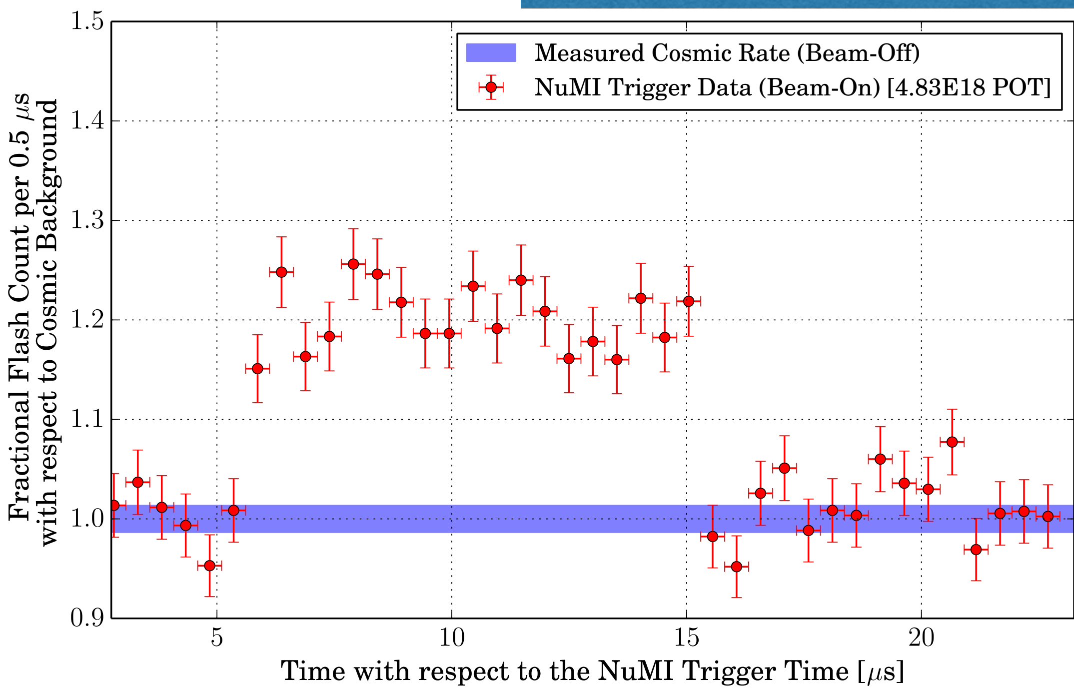
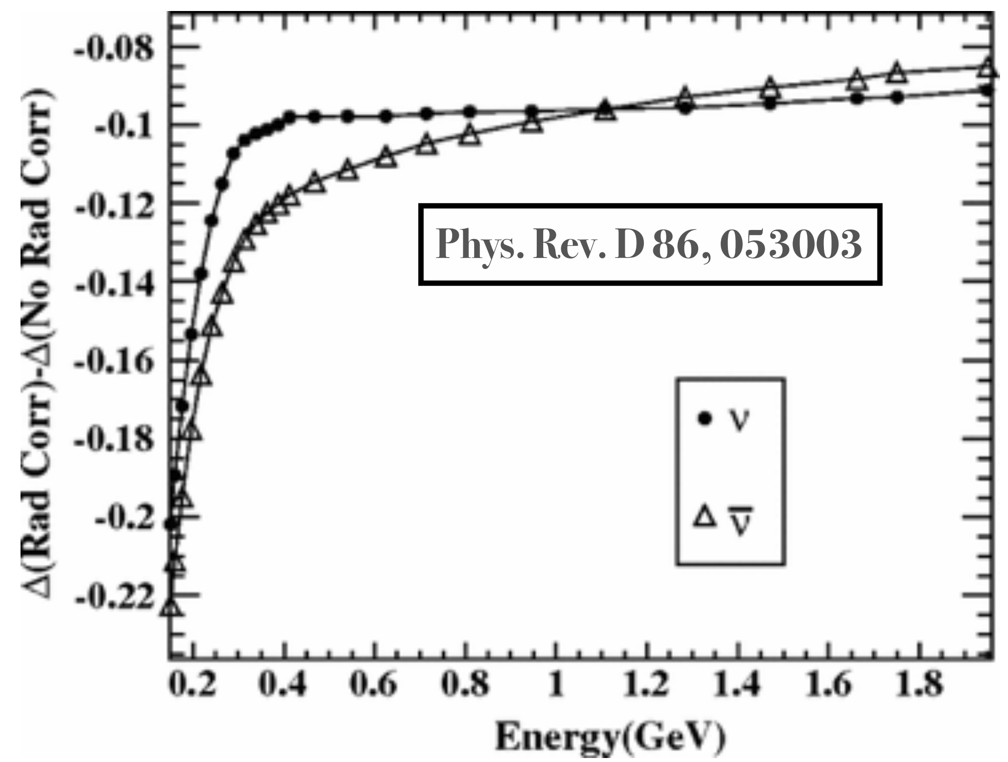
Double the beam, double the fun!

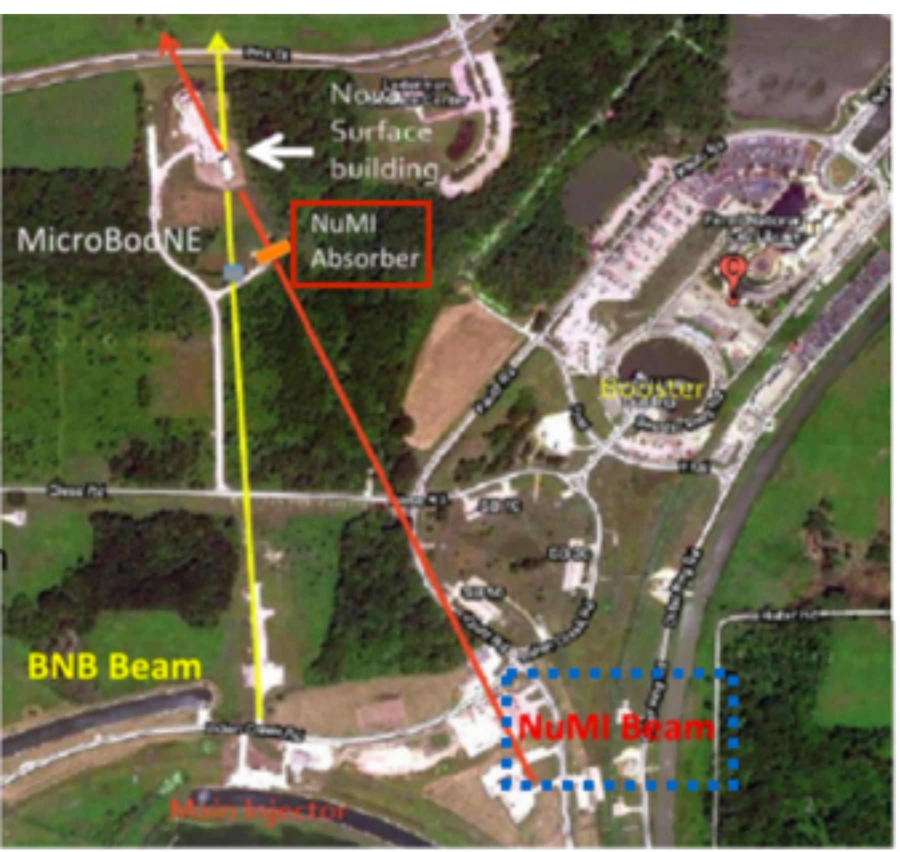
NuMI: On the way to constrain ν_e-Argon interactions

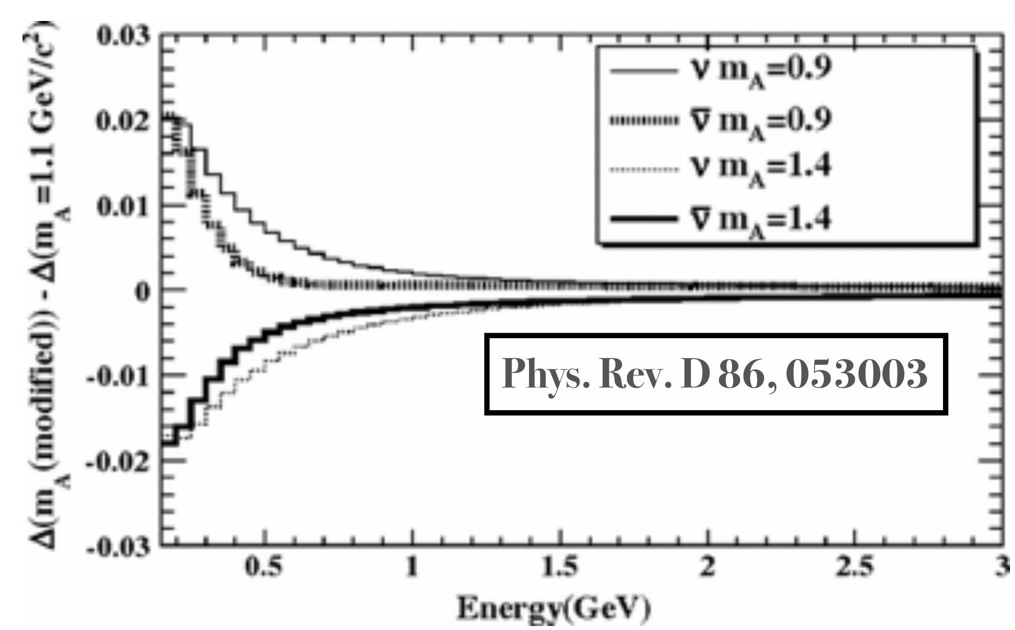
MicroBooNE receives 2 different neutrino beams: BNB but also NuMI

NuMI arrives off-axis ~6 degrees wrt the detector









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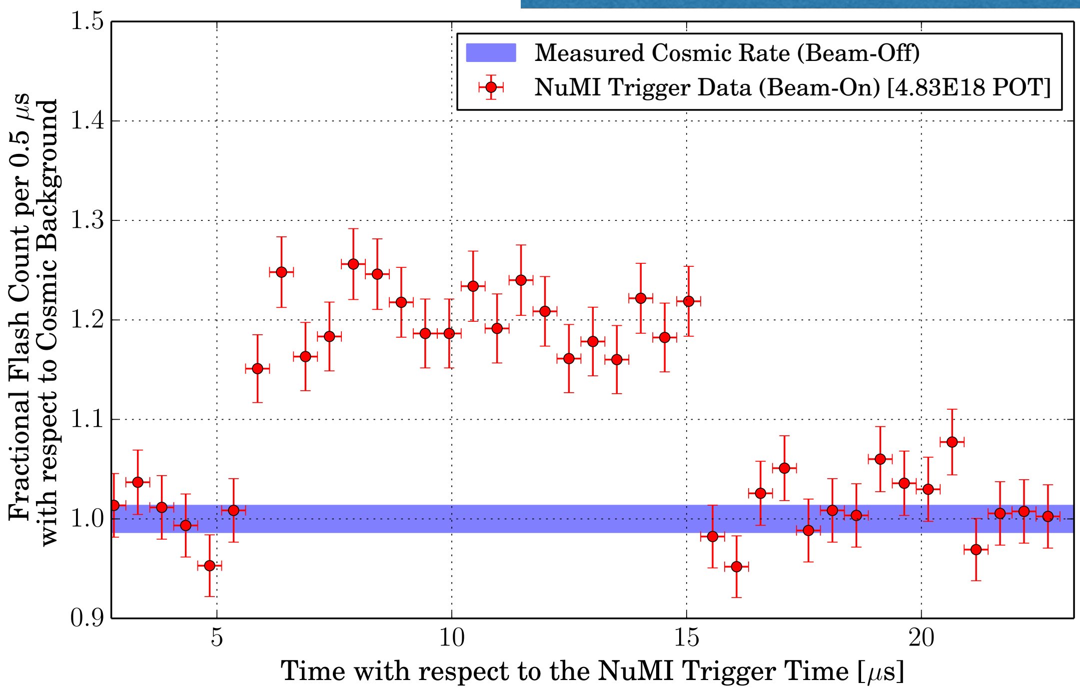
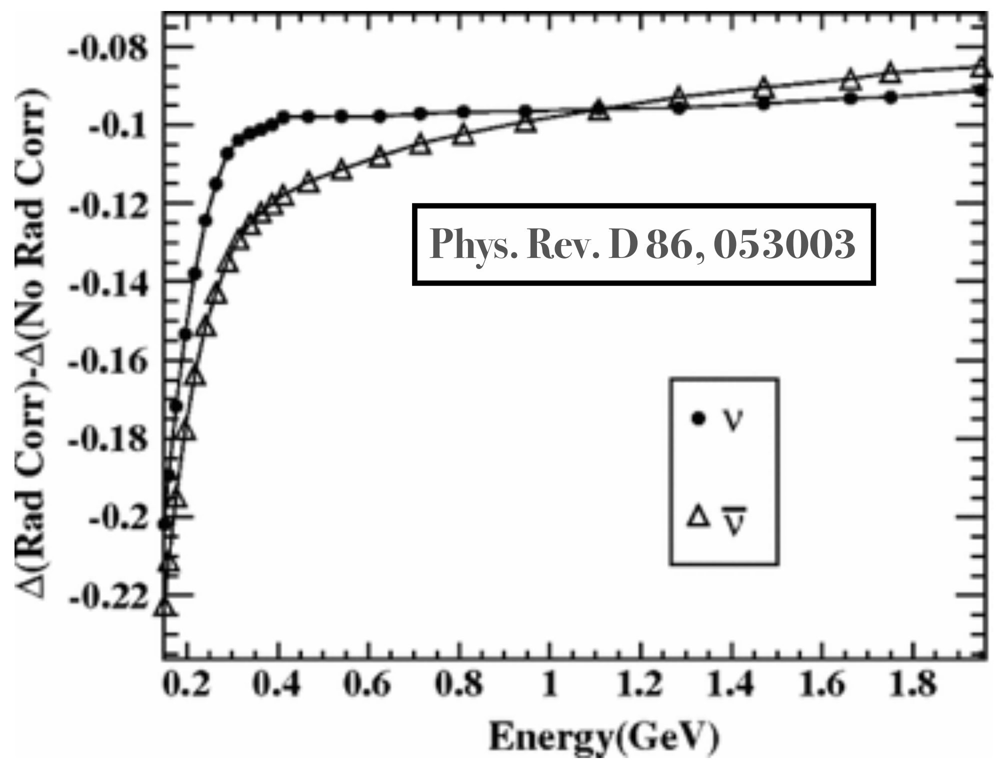
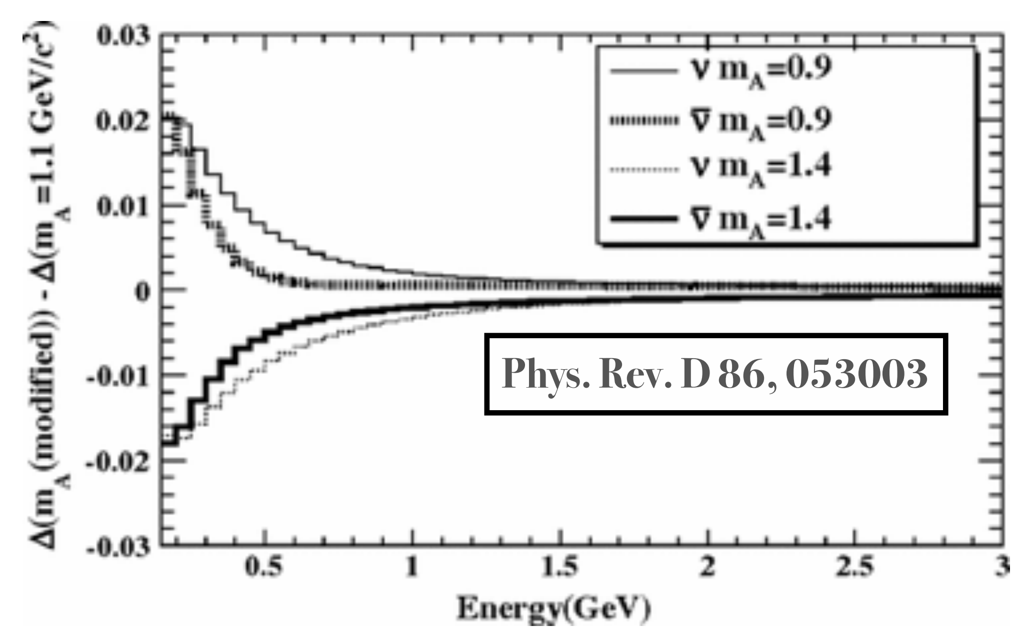




Ongoing measurement on ν_e CC inclusive cross section.

- Fundamental to have a first comprehension of ν_e-Argon interactions and their uncertainties
- Understand ν_e / ν_μ
- Fully unblinded dataset to test our reconstruction



Considering external data: $e^{+/-}$, ν & hadron

External data has been extensively used by both **MC builders** (to parametrize models) and **data analyzers** (when trying to get their uncertainties). Sometimes (usually) the MC builders and the data analyzers use the **same data sets**.

Commonly used data:

- **ν-nucleus**
- **electron-nucleus**

We need to understand exactly how these models have been parametrized to argon and how uncertainties have been estimated.

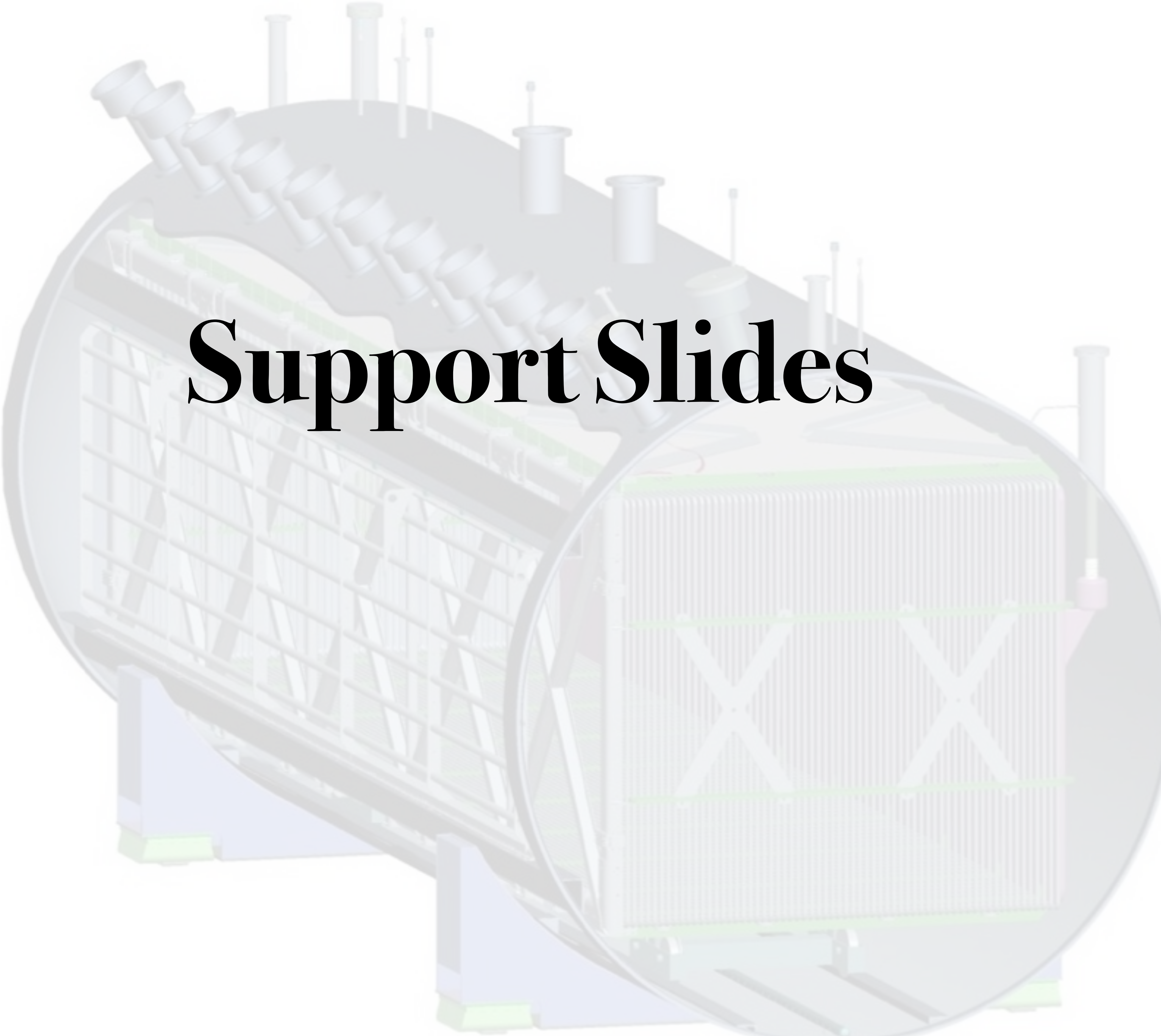
A singular problem appears with hadron-nucleus data. This data correspond to hadron-nucleus cross sections to the outer shell of the nucleus, while ν-induced hadron production may corresponds to the inner shells on where hadron cross sections may be different.

Warning: personal message

Summary

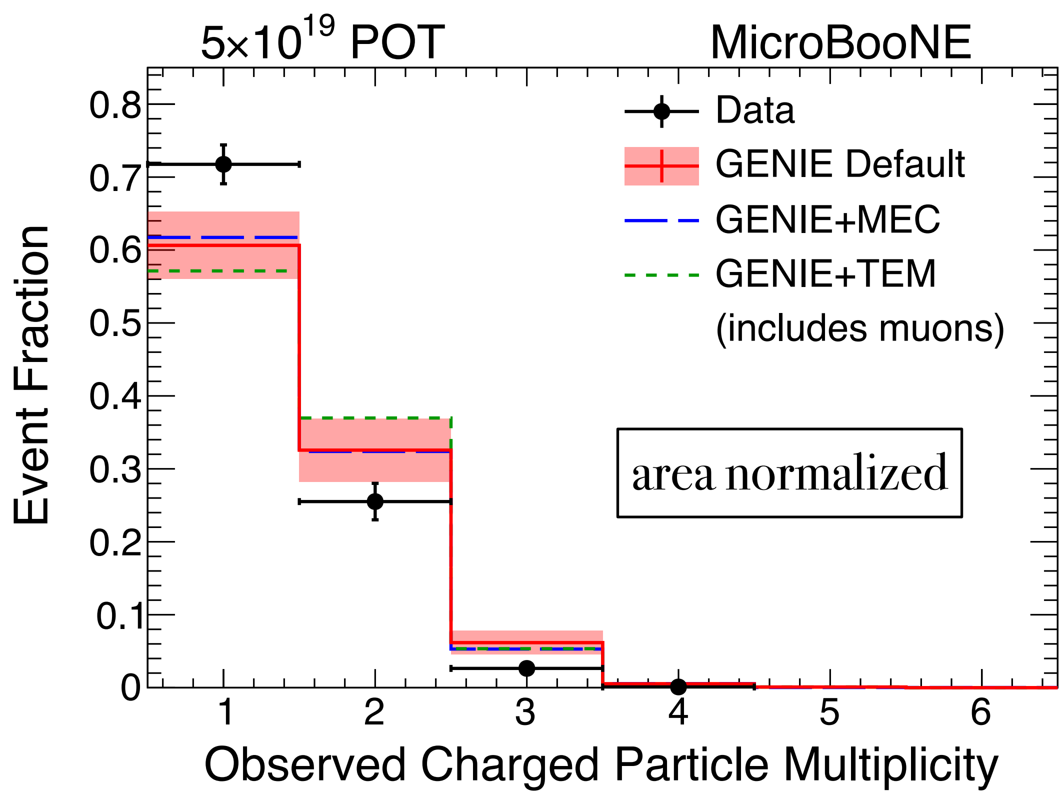
- MicroBooNE has built its path to get into its **first physics results**. Lot of work on simulation, reconstruction and calibration has been done and more improvements are coming as we talk.
- Our main goal is to identify the origin of the observed anomalies presented by LSND and MiniBooNE.
- It builds the **foundations of the knowledge required for DUNE**. Both in reconstruction and ν-Ar scattering.
- SBND will collect more data (**1 month SBND data=1 year MicroBooNE data**) to allow for strong constraints in neutrino-Ar.
- Future work concentrates on ν_μ CC measurements with enhanced proton selections.
- We are all compromised to keep lowering the particle detection threshold and resolution improvements to the detector limits, and offer **un-precedented high-acceptance high-precision results**.
- Today, we present our first cross section results, **ν_μ CC charged particle multiplicities**, **differential νμ CC inclusive** and **total ν_μ CCπ^0**.
- But… this is just the beginning.

Support Slides



ν_μ CC charged particle multiplicity measurement

Its main goal is to understand how our direct observables (final state particles) are represented by the simulation.
Represents a first big step on understanding how a final event *visible energy* measurement can be biased due to excess/deficit of final state particles. Strongly sensitive to FSI.
For this first measurement, a conservative particle threshold has been applied.



pionKE> 31MeV
proton KE> 69MeV

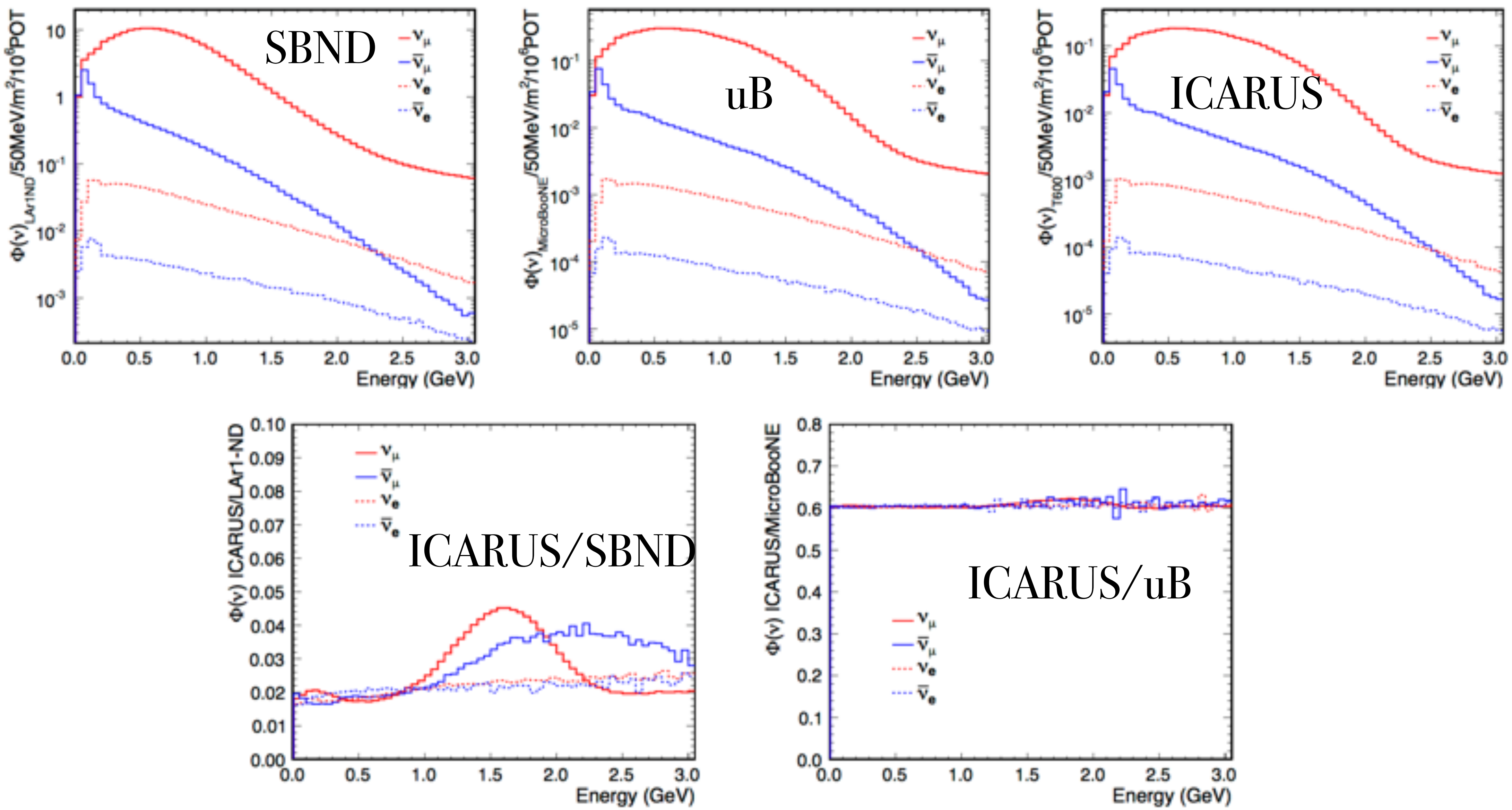
muon containment: muon KE <1.2GeV

“Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions”, arXiv:1805.06887, submitted to PRD (2018)

ν Flux @ SBND, MicroBooNE and ICARUS

8 GeV Protons from BNB

Almost pure ν_μ beam (0.5% intrinsic ν_e contamination at uB)



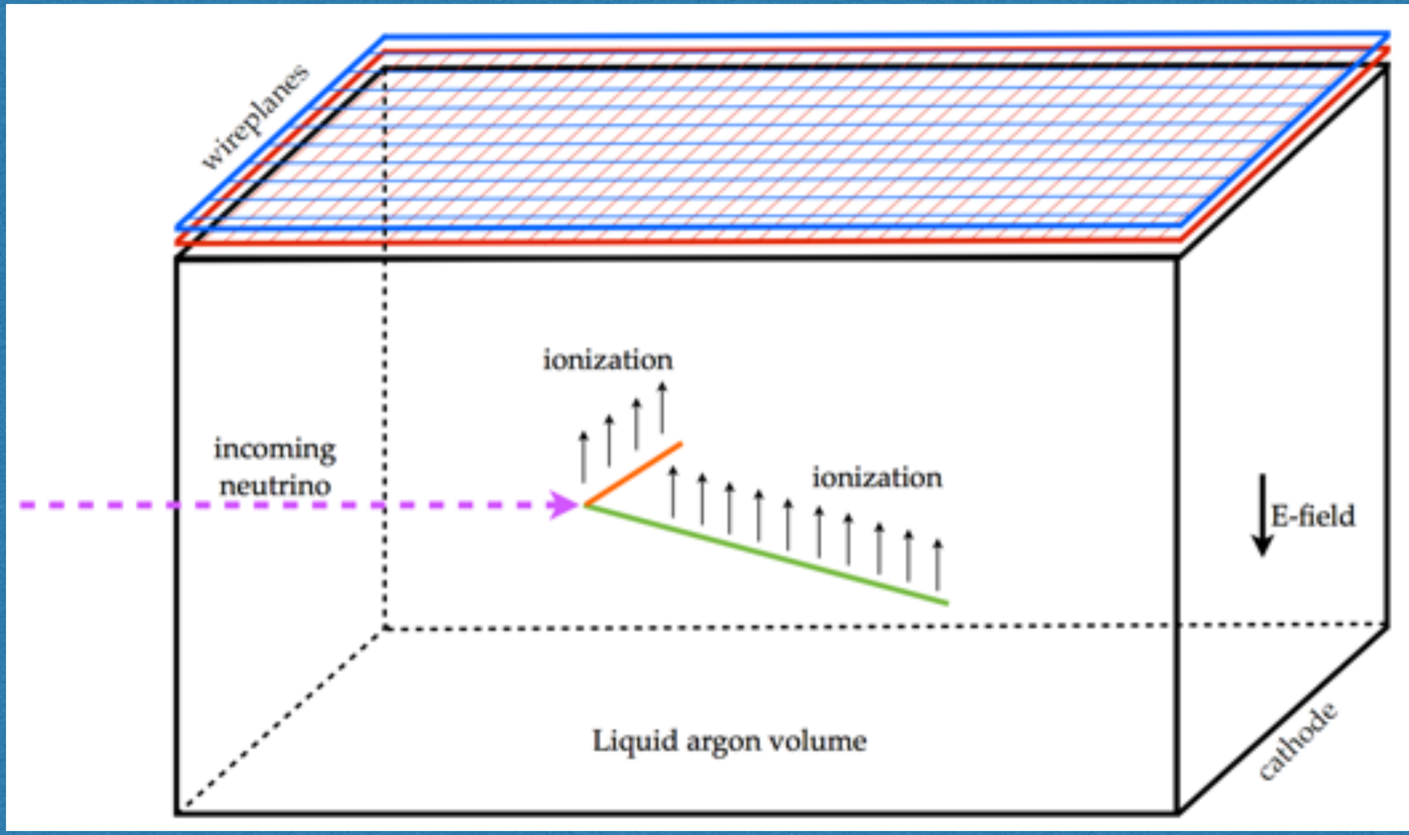
Same ν beam at different detection locations: different spectrum

Same detector technology: very similar detection thresholds, resolutions and detector uncertainties

Sharing simulation, reconstruction and analysis techniques

Precision era: Liquid Argon TPC

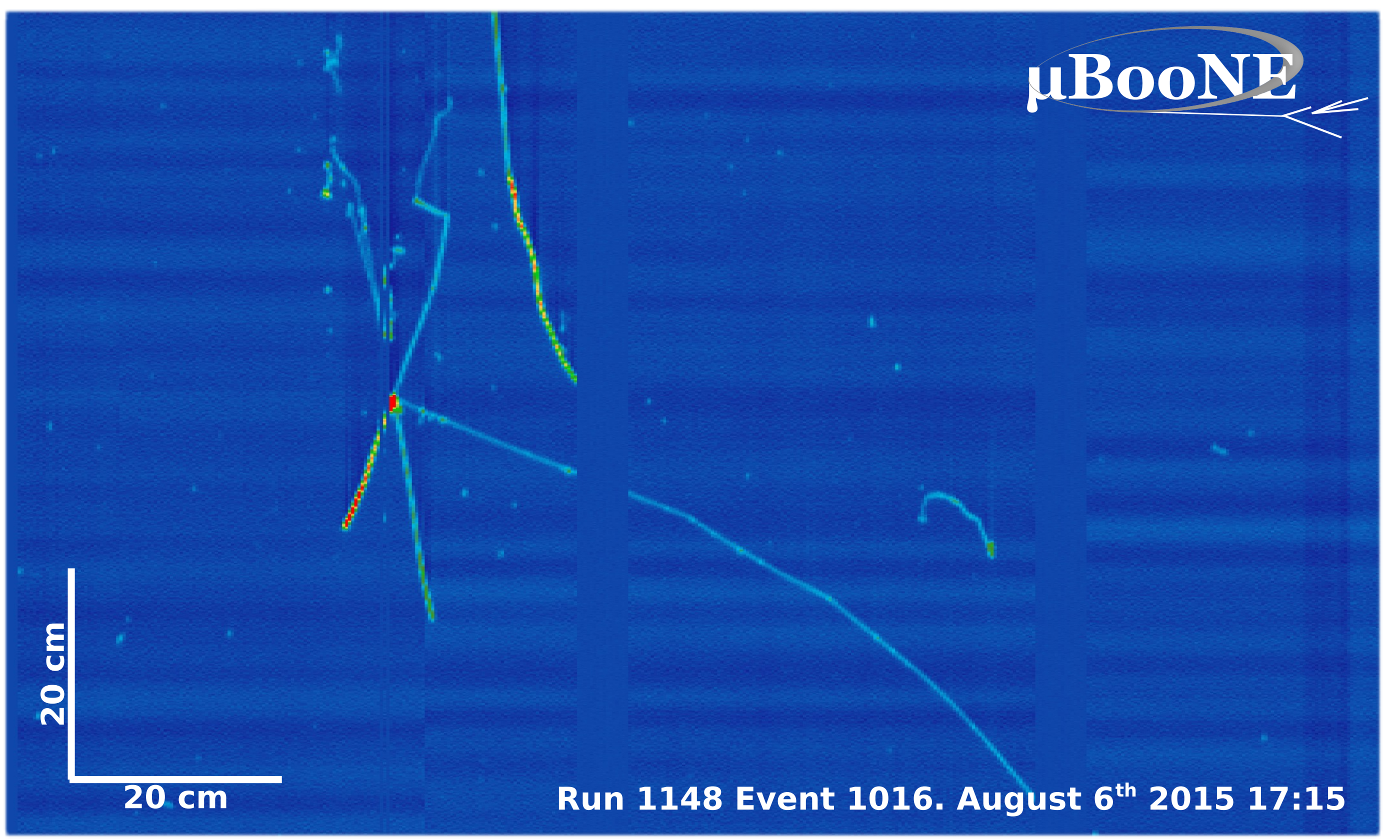
- Ionization from traversing charged particles is drifted along E-field to the segmented wire planes.
  - argon ionizes easily, ~70 ke/cm (@500 V/cm)
- Wire pulse timing information is combined with known drift speed to determine drift-direction coordinate.
- Calorimetry information is extracted from wire pulse characteristics.
- Abundant **scintillation light**, which LAr is transparent to, also available for collection and triggering.
  - **40k γ/MeV @null E-field**
- Argon is **40%** more dense than water.
- **1%** abundance in the atmosphere.

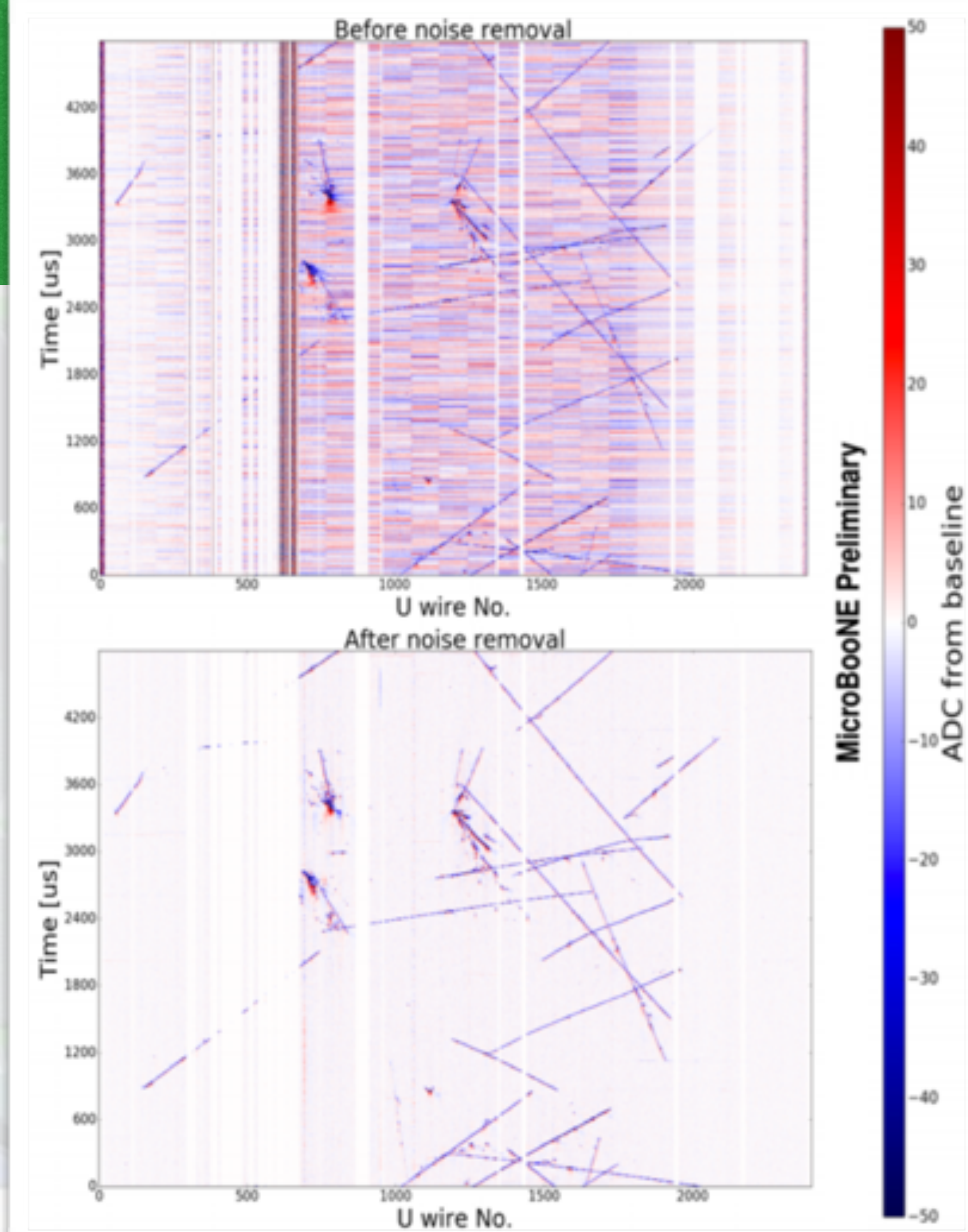


MicroBooNE TPC

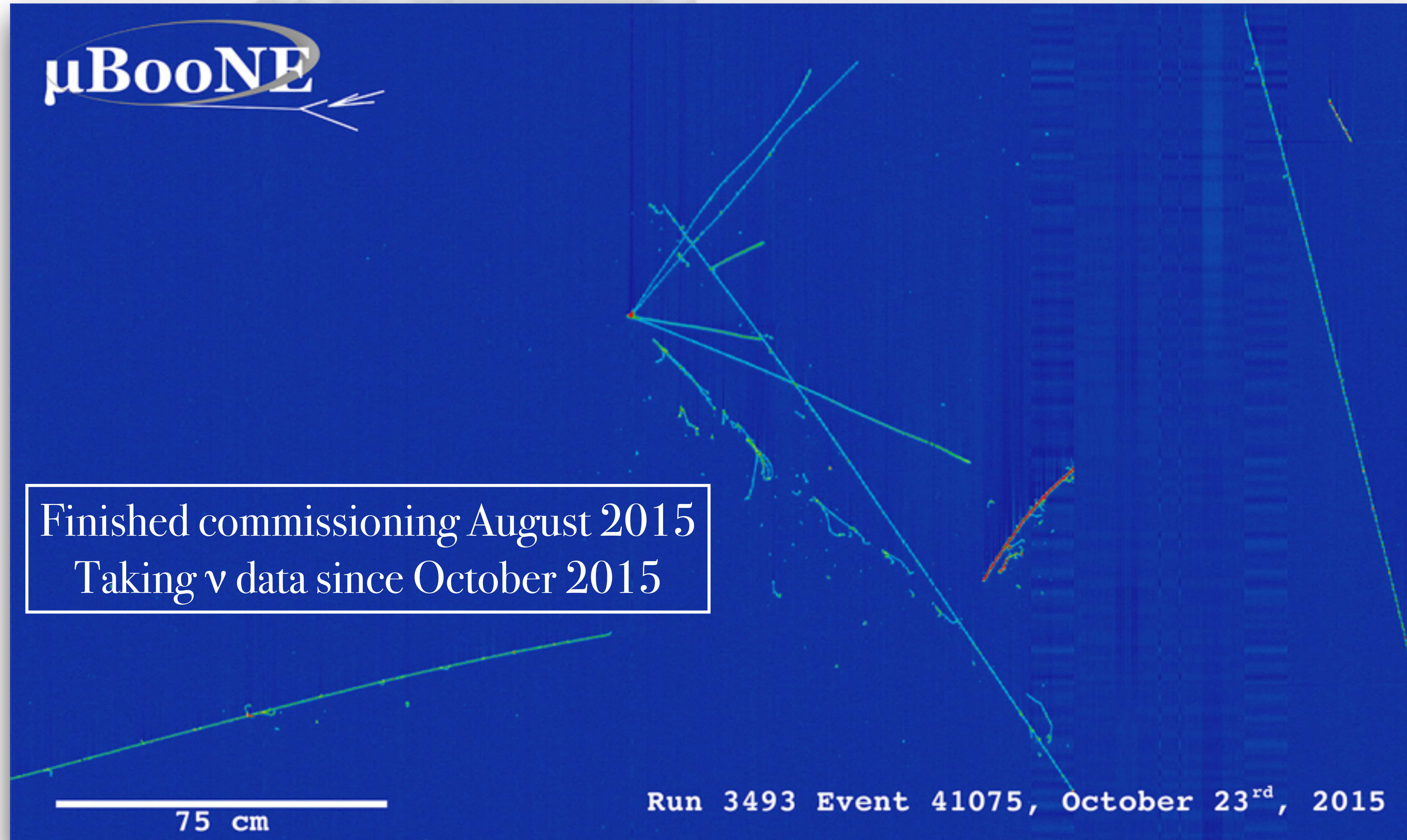
MICROBOONE-NOTE-1016-PUB

- Coherent noise over group of channels
  - This noise is associated to a voltage regulator on a warm service board
  - With software filtering we are able to improve signal-to-noise by factor of 2
- Signal-to-noise ratio after software noise filtering
- U plane 15.8 : 1
- V plane 12.9 : 1
- Y plane 45.3 : 1

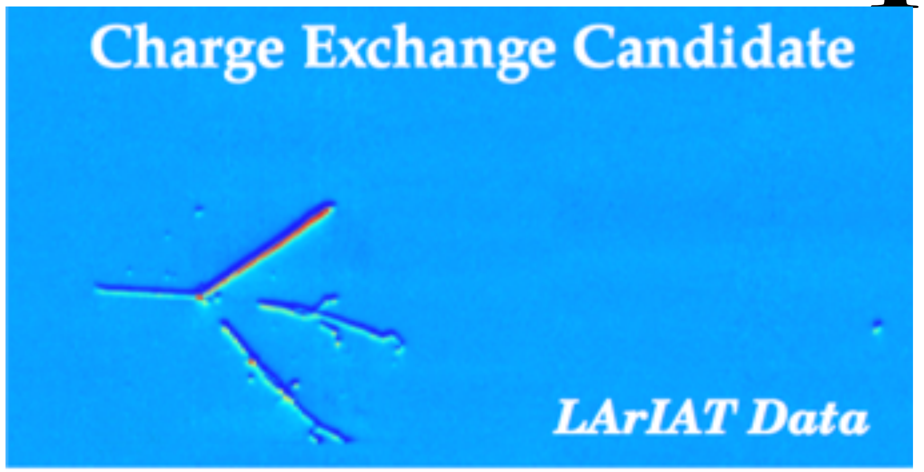


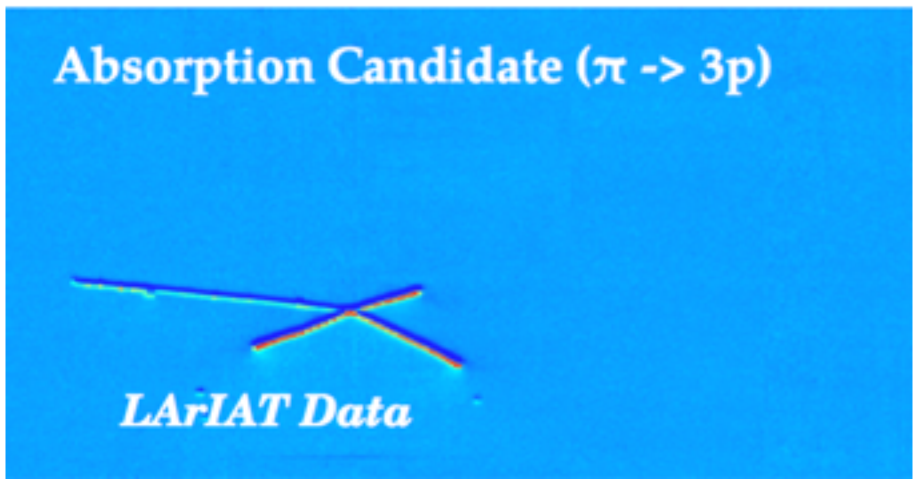


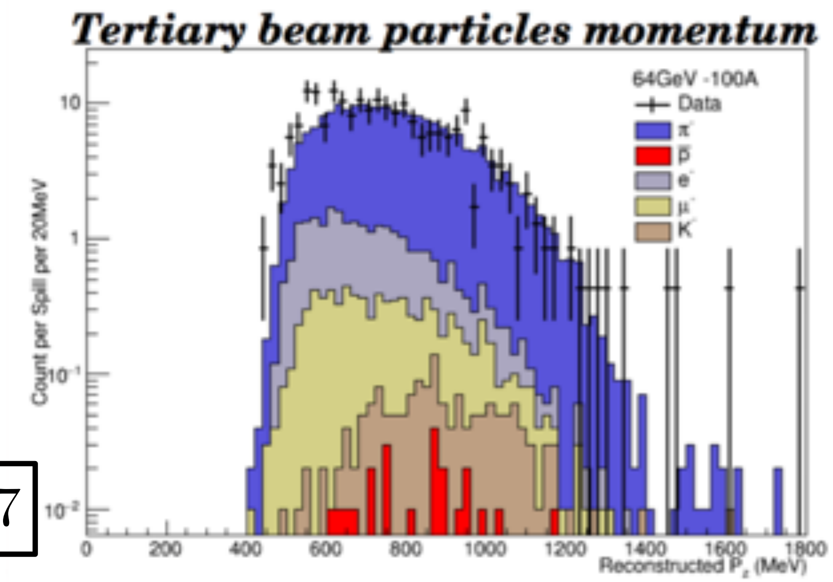
MicroBooNE Physics



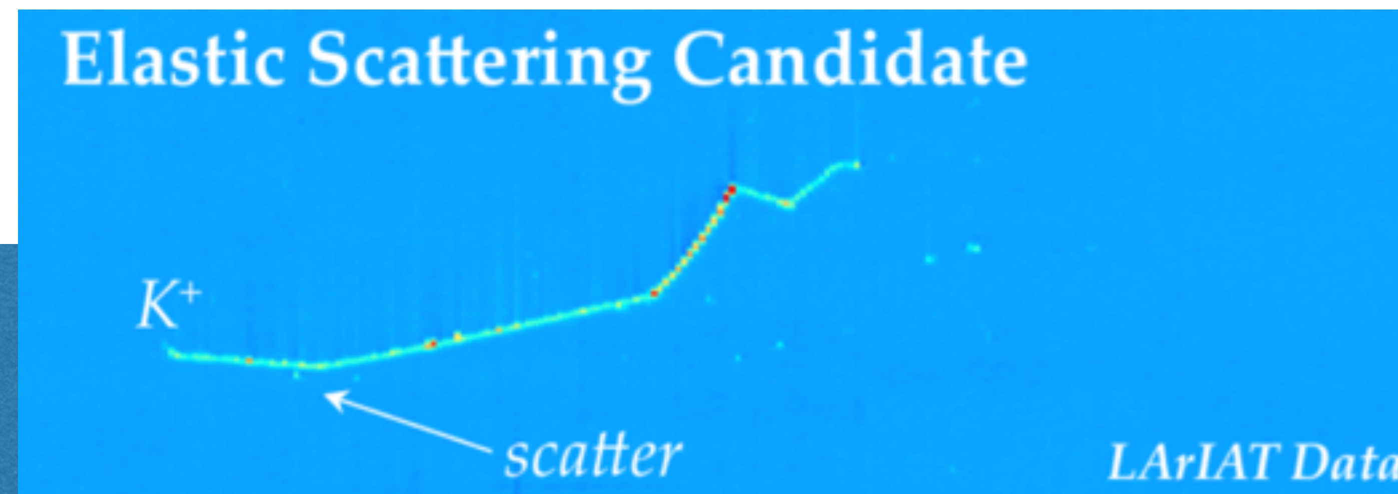
LArIAT: Liquid Argon In A Test beam







J. Assadi, NuINT'17



Experiments such as **LArIAT** provide a wealth of data with direct applications for studying **secondary interaction** processes.

As well can be used for **FSI estimations**, <u>only if the FSI model adopted distinguishes if that the FSI interaction has different cross section depending of the shell structure and assuming that this external data only constraints the last shell values</u>.